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AERONAUTICAL DESIGN STANDARD

HANDBOOK

FOR

CONDITION BASED MAINTENANCE SYSTEMS

FOR US ARMY AIRCRAFT

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CONDITION BASED MAINTENANCE SYSTEMS FOR US ARMY AIRCRAFT

UNITED STATES ARMY AVIATION AND MISSILE COMMAND

AVIATION ENGINEERING DIRECTORATE

REDSTONE ARSENAL, ALABAMA

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CERTIFICATION RECORD

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Rationale for Certification

General Type	Decision (√)	Certification
Specification		Performance
		Detail
Standard		Interface Standard
		Standard Practice
		Design Standard
		Test Method Standard
		Process Standard
Handbook	√	Handbook (Non-Mandatory Use)

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AMCOM Director, Condition Based Maintenance Christopher Smith			5 Jan 09
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FOREWORD

1. This document is approved for use by the U.S Army Research, Development, and Engineering Command, Aviation Engineering Directorate and is available for use by all agencies and departments of the Department of Defense.

2. This Handbook describes the Army's CBM System and defines the overall guidance necessary to achieve CBM Goals. The Handbook contains some proven methods to achieve CBM functional objectives, but these suggested methods should not be considered to be the sole means to achieve these objectives. The Handbook is intended for use by:

    a. Aircraft life cycle management personnel defining guidance for CBM implementation in existing or new acquisition programs. This Handbook should be used as a foundation for program specific guidance for CBM to ensure that the resulting program meets Army requirements for sustained airworthiness through maintenance methods and logistics systems.

    b. Contractors incorporating CBM into existing or new acquisition programs for Army aviation equipment. In most cases, a CBM management plan should be submitted to the government as part of the Statement of Work (SOW) for the acquisition, as required by the Request for Proposal (RFP) or Contract. The management plan should apply to aircraft systems, subsystems and the vehicle's airframe. The management plan will outline the contractor's proposed methods for achieving CBM goals listed in the RFP and the management control actions which will guide implementation.

3. This document provides guidance and standards to be used in development of the data, software and equipment to support Condition Based Maintenance (CBM) for systems, subsystems and components of US Army aircraft. The purpose of Condition Based Maintenance is to take maintenance action on equipment where there is evidence of need. Maintenance guidance are based on the condition or status of the equipment instead of specified calendar or time based limits such as Maximum Operating Time (MOT) while still preserving the system baseline risk. This Design Handbook accomplishes that goal by describing elements that enable the issue of CBM Credits, or modified inspection and removal criteria of components based on measured condition and actual usage. This adjustment applies to either legacy systems with retro-fitted and validated CBM Systems as well as new systems developed with CBM as initial design requirements. These adjustments can either decrease or increase the component's installed life, depending on the severity of operational use and the detection of faults.

4. Comments, suggestions, or questions on this document should be addressed to Commander, U. S. Army Research, Development and Engineering Command, Aviation and Missile Research, Development and Engineering Center, AMSRD-AMR-AE, Huntsville, AL 35898. Since contact information can change, one should verify the currency of this address information using the ASSIST online database at http://assist.daps.dla.mil/online/start/.

5. Specific technical questions may be addressed to the following office:

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TABLE OF CONTENTS

1 Scope

This document, an Aeronautical Design Standard (ADS) Handbook, provides guidance and defines standard practices for the design and testing of all elements of the Condition Based Maintenance (CBM) System, including analytical methods, sensors, data acquisition hardware, signal processing software, and data management standards necessary to support the use of CBM as the maintenance approach to sustain and maintain systems, subsystems, and components of Army air items. This includes the process of defining CBM Credits (modified inspection and removal criteria of components based on measured condition and actual usage) resulting from CBM implementation as well as Airworthiness Credits. The document is organized with a main body associated with general overarching guidance, and appendices governing more specific guidance arising from application of technical processes.

There are four goals for the implementation of CBM: (1) reducing burdensome maintenance tasks currently required to assure continued airworthiness, (2) increasing aircraft availability, (3) improving flight safety, and (4) reducing sustainment costs. Any changes to maintenance practices identified to meet these goals must be technically reviewed to ensure there has been no change to baseline risk. This document provides specific technical guidance for the CBM to ensure the resulting CBM system is effective and poses no greater risk than the original baseline design.

The functional guidance for a CBM system are intended to include: (1) engine monitoring, (2) dynamic system component monitoring, (3) structural monitoring, (4) exceedance recording, (5) usage monitoring (6) electronic logbook interface. These functional capabilities are intended to implement CBM on all Army aircraft.

2 Applicable Documents

2.1 General.

The documents listed below are not necessarily all of the documents referenced herein, but are those needed to understand the information provided by this handbook.

2.1.1 Government Documents

Specifications, standards, and handbooks. The following specifications, standards, and handbooks form a part of this document to the extent specified herein."

- MIL-STD-1553B. Digital Time Division Command/Response Multiplex Data Bus. <http://assist.daps.dla.mil/quicksearch/basic_profile.cfm?ident_number=36973>

(Copies of these documents are available online at http://assist.daps.dla.mil/quicksearch/ or from the Standardization Document Order Desk, 700 Robbins Avenue, Building 4D, Philadelphia, PA 19111-5094.)

2.1.2 Other Government documents, drawings, and publications.

The following other Government documents, drawings, and publications form a part of this document to the extent specified herein."

- Army Regulation 70-62. "Airworthiness Qualification of Aircraft Systems." 21 May 2007.
- Army Pamphlet 750-40. "Guide to RCM for Fielded Equipment." 1980.
- DoDI 4151.22. "Condition Based Maintenance Plus (CBM+) for Materiel Maintenance." Department of Defense Instruction Number 4151.22. 2 December 2007.

Copies of these documents are available online at
http://www.army.mil/usapa/epubs/pdf/r70_62.pdf ;
http://www.dtic.mil/whs/directives/corres/pdf/415122p.pdf ;
http://www.apd.army.mil/USAPA_PUB_pubrange_P.asp?valueAD=Pam+-+DA+Pamphlet

Non-Government publications. The following documents form a part of this document to the extent specified herein."

- ISO 13374:2003. Condition Monitoring and Diagnostics of Machines.
- MIMOSA Open Systems Architecture for Condition Based Maintenance, v3.2.
- Felker, Douglas. "PM/FM Matrix & CBM Gap Analysis in Reliability Centered Maintenance." Presented to the 2006 DoD Maintenance Symposium.
- Canaday, Henry. "Hunting for Productivity Gains." Aviation Week and Space Technology. September 10, 2004.

- RTCA DO-178B. Software Considerations in Airborne Systems and Equipment Certification.

- RTCA DO-200A. Standards for Processing Aeronautical Data

Copies of these documents are available at http://www.iso.org/iso/iso_catalogue.htm; http://www.mimosa.org/

3 Definitions

Airworthiness: A demonstrated capability of an aircraft or aircraft subsystem or component to function satisfactorily when used and maintained within prescribed limits (Ref AR 70-62).

Airworthiness Credit: An airworthiness credit is any change to flight operating procedures, flight envelope & limitations, component retirement times, serviceability criteria or emergency procedures. These changes can either be positive or negative (i.e. extended or reduced component retirement times, reduced maximum speed or maneuverability, increased or decreased over torque or over speed limits). The change can be specific to a unique item (component or part), or any group of items or aircraft as defined in the respective Airworthiness Release (AWR).

Baseline Risk: The established acceptable risk in production, operations, and maintenance procedures reflected in frozen planning, the Operator's Manuals, and the Maintenance Manuals for that aircraft. Maintenance procedures include all required condition inspections with intervals, retirement times, and Time Between Overhauls (TBOs).

CBM Credit: Any change to the scheduled maintenance interval specified by engineering for a specific end item or component, such as an extension or reduction in inspection intervals or Maximum Operating Times (MOTS) established for the baseline system prior to incorporation of CBM as the approved maintenance approach. (For example, a legacy aircraft with a 2,000 MOT for a drive system component can establish a change to the MOT for an installed component for which CBM CI values remain below specified limits and the unit remains installed on a CBM equipped aircraft.) Often, CBM Credits may be communicated through an Airworthiness Release (AWR).

Condition Indicator (CI): A measure of detectable phenomena, derived from sensors that show a change in physical properties related to a specific failure mode or fault.

Confidence – The probability that the true reliability is at least as high as what is stated, equal to one minus the probability of a false negative. The target confidence is 90%.

False Positive – Failure mode is detected but not found by inspection; condition does not match recorded CI level (yellow or red CI = healthy component)

False Negative – Failure mode is not detected but is found to exist by inspection; condition does not match recorded CI level (green CI = faulty component)

Health Indicator (HI): An indicator for needed maintenance action resulting from the combination of one or more CI values.

Health Monitoring: Equipment, techniques or procedures by which selected incipient failure or degradation can be determined.

Reliability – As used in this ADS, reliability is the probability that both true positives and true negatives will be correctly identified by the CBM system. The target reliability is 90% for true positive and true negative detection.

Remaining Useful Life (RUL): An estimate of the point at which maintenance action is required to restore the affected system or component to normal operations. The maintenance action required to restore normal operations may include inspection, adjustment or replacement of the item. The end of useful life of an end item or component may be well before catastrophic failure if the consequence of material failure creates the potential for additional damage or compromise to continued airworthiness of the aircraft.

Standard Deviation – A measure of the amount by which measurements deviate from their mean.

True Positive – Failure mode is detected with condition verified by inspection and matching recorded CI level (yellow or red CI = faulty component).

True Negative – Failure mode is not detected with condition verified by inspection and matching recorded CI level (green CI = healthy component)

Usage Monitoring: Equipment, techniques and/or procedures by which selected aspects of service [flight] history can be determined.

4 General Guidance

4.1 Background

DoD policy on maintenance of aviation equipment has employed Reliability Centered Maintenance (RCM) analysis and methods to avoid the consequences of material failure. The structured processes of RCM have been part of army aviation for decades, including Army Pamphlet 750-40 "Guide to RCM for Fielded Equipment," issued in 1980 and a number of subsequent directives. RCM analysis provides a basis for developing requirements for CBM through a process known as "Gap Analysis."[1]

Condition Based Maintenance (CBM) is a set of maintenance processes and capabilities derived primarily from real-time assessment of weapon system condition obtained from embedded sensors and/or external test and measurements using portable equipment. CBM is dependent on the collection of data from sensors and the processing, analysis, and correlation of that data to material conditions that require maintenance actions. Maintenance actions are essential to the sustainment of material to standards that insure continued airworthiness.

Data provide the essential core of CBM, so standards and decisions regarding data and their collection, transmission, storage, and processing dominate the requirements for CBM system development. CBM has global reach and multi-systems breadth, applying to everything from fixed industrial equipment to air and ground vehicles of all types. This breadth and scope has motivated the development of an international overarching standard for CBM. The standard, known as ISO 13374:2003, "Condition Monitoring and Diagnostics of Machines," provides the framework for CBM.

This handbook has been amplified by the Machinery Information Management Open Standards Alliance (MIMOSA), a United States organization of industry and government, and published as the MIMOSA Open Systems Architecture for Condition Based Maintenance (OSA CBM) v3.2. The standard is embodied in the requirements for CBM found in the Common Logistics Environment (CLOE) component of the Army's information architecture for the Future Logistics Enterprise. The ISO standard, the OSA CBM standard, and CLOE all adopt the framework shown in Figure 1 for the information flow supporting CBM with **data flowing from bottom to top**. This document, however, considers the application of CBM only to Army air items (Aircraft and Unmanned Aerial Vehicles).

[1] Felcer, Douglas, "PM/FM Matrix & CBM Gap Analysis in Reliability Centered Maintenance," presented to the 2006 DoD Maintenance Symposium.

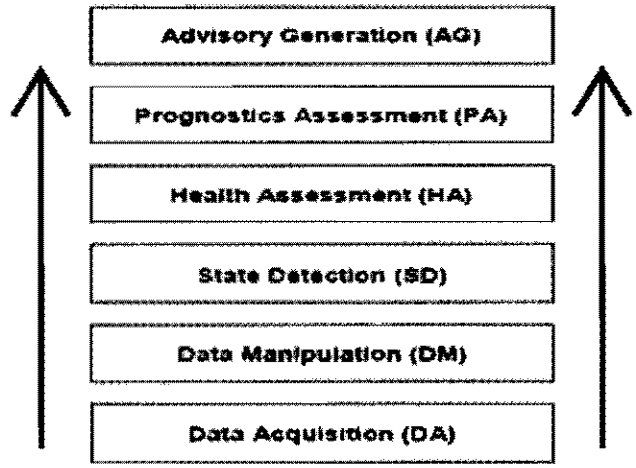

Figure 1: ISO-13374 Defined Data Processing and Information Flow

4.2 General Guidance

CBM practice is enabled through three basic methodologies: (1) embedded diagnostics for components that have specific detectable faults (e.g., drive systems components with fault indicators derived from vibratory signature changes and sensors suitable for tracking corrosion damage), and (2) fatigue life management, through estimating the effect of specific usage in flight states that incur fatigue damage as determined through fatigue testing, modeling, and simulation and (3) usage monitoring, which may derive the need for maintenance based on parameters such as the number of power-on cycles, the time accumulated above a specific parameter value or the number of discrete events accumulate. Within this context, specific guidance is provided where benefits can be derived.

In the context of data management on the platform, every effort should be made to conform to existing vehicle architectures and common military standards for data acquisition and collection. Military vehicles typically use MIL-STD-1553B, Digital Time Division Command/Response Multiplex Data Bus[2], for sending multiple data streams to vehicle processors. As the use of commercial off-the-shelf (COTS) hardware and software has become more prevalent, the use of commercial standards for data transfer (such as Ethernet, TCP/IP and USB) may be accepted as suitable design standards for CBM in aviation systems.

4.2.1 Embedded Diagnostics

Health and Usage Monitoring Systems (HUMS) have evolved over the past several decades in parallel with the concepts of CBM. They have expanded from measuring the usage of the systems (time, flight parameters, and sampling of performance indicators such as temperature

[2] MIL-STD-1553B. Digital Time Division Command/Response Multiplex Data Bus. 15 January 1996. See also: <http://assist.daps.dla.mil/quicksearch/basic_profile.cfm?ident_number=36973>.

and pressure) to elementary forms of fault detection through signal processing. The elementary signal processing typically recorded instances of operation beyond prescribed limits (known as "exceedances"), which then could be used as inputs to troubleshooting or inspection actions to restore system operation. This combination of sensors and signal processing (known as "embedded diagnostics") represents a capability to provide the item's condition and need for maintenance action. When this capability is extended to CBM functionality (state detection and prognosis assessment), it must have the following general characteristics:

- Sensor Technology: Sensors must have high reliability and high accuracy. There is no intent for recurring calibration of these sensors.

- Data Acquisition: Onboard data acquisition hardware must have high reliability and accurate data transfer (See Appendix E).

- Algorithms: Fault detection algorithms are applied to the basic acquired data to provide condition and/or health indicators. Validation and verification of the Condition Indicators (CIs) and Health Indicators (HIs) included in the CBM system are required in order to establish maintenance and airworthiness credits. Basic properties of the algorithms are: (1) sensitivity to faulted condition, and (2) insensitivity to conditions other than faults. The algorithms and methodology must demonstrate the ability to account for exceedances, missing or invalid data.

Specific guidance for HUMS used as integral parts of the CBM System are found in Appendix A. HUMS operation during flight is essential to gathering data for CBM System use, but is not flight critical or mission critical when it is an independent system which obtains data from primary aircraft systems and subsystems. When this independence exists, the system should be maintained and repaired as soon as practical to avoid significant data loss and degradation of CBM benefits. As technology advances, system design may lead to more comprehensive integration of HUMS with mission systems. The extent of that future integration may lead to HUMS being part of mission or flight critical equipment or software. In this case, the HUMS bears the same priority as mission or flight critical equipment relative to the requirement to restore its proper operation.

4.2.2 Fatigue Damage Monitoring

Fatigue damage is estimated through calculations which use estimates of loads on airframe components experienced during flight. These loads are dependent on environmental conditions (e.g., temperature and altitude) and aircraft maneuver parameters (i.e.: gross weight, center of gravity, power applied, and accelerations). To establish these loads, algorithms which determine the aircraft maneuver parameters, known as regime recognition algorithms, are used to take these parameters and map them to known aircraft maneuvers. In order to establish regime recognition algorithms as the basis for loads and fatigue life adjustment, the algorithms must be validated through flight testing.

Legacy aircraft operating without CBM capabilities typically use assumed usage and Safe Life calculation techniques to ensure airworthiness. Structural loading of the aircraft in flight, including instances which are beyond prescribed limits (i.e.: exceedances) for the aircraft or its components on legacy platforms typically use a rudimentary sensor or data from a cockpit display with required post-flight inspection as the means to assess damage. The advent of data collection from sensors onboard the aircraft, typically performed onboard an aircraft by a Digital Source Collector (DSC) and/or Flight Data Recorder (FDR), enable methods that improve accuracy of the previous detection and assessment methods. The improvement is due to the use of actual usage or measured loads rather than calculations based on assumptions made during the developmental design phase of the acquisition.

Regime Recognition (Actual Usage Detection and Measurement)

Accurate detection and measurement of flight regimes experienced by the aircraft over time enable two levels of refinement for fatigue damage management: (1) the baseline "worst case" usage spectrum can be refined over time as the actual mission profiles and mission usage can be compared to the original design assumptions, and (2) running damage assessment estimates can be based on specific aircraft flight history instead of the baseline "worst case" for the total aircraft population. Both levels of refinement require data management infrastructure that can relate aircraft regime recognition and flight history data to individual components and items which are tracked by serial part number. Knowledge of the actual aircraft usage can be used to refine the baseline 'worst case' usage spectrum used to determine the aircraft service schedules and component retirement times. The refinement of the "worst case" usage spectrum, depending on actual usage, could result in improved safety and/or reduced cost. From experience in the airline industry, the additional burden created by requirements to collect and archive flight data and aircraft configuration are offset by the benefits of granting CBM credits for specific aircraft or items based on their actual condition and operational history.[3] The criteria for acceptance of airworthiness credits from a fatigue life management point of view are provided in Appendix F.

The refined usage spectrum accounts for global changes in usage of the aircraft and may be refined for specific periods of operation. An example is the operation in countries where the mean altitude, temperature, or exposure to hazards can be characterized. The use of DSC data to establish a new baseline usage spectrum is the preferred method (compared with pilot survey method).

The running damage assessment is more dependent on specific systems to track usage by part serial number. Specifics for the implementation of the running damage assessment are given in Appendix B: Regime Recognition/Flight State Classification with Validation of Regime Recognition Algorithms.

Fatigue Damage Remediation

Remediation may be used to address components that are found to be routinely removed from service without reaching the fatigue safe life. The process of remediation involves the identification of removal causes that most frequently occur. The ability to change the "tolerance" allows consideration of additional usage. Details for implementation of remediation

[3] Canaday, Henry, "Hunting for Productivity Gains," Aviation Week and Space Technology, September 10, 2004.

are found in Appendix F. When remediation action is taken on a part as part of a repair that affects its fatigue life, such as removing deep scratches from a serialized dynamic component, the modified fatigue life must be assigned to that specific serial number and retained until that serial numbered part is retired and removed from inventory.

4.2.3 Ground Based Equipment and Information Technology

The use of data to modify maintenance practice is the heart of CBM. As such, the ground based equipment that is used to complete the data processing and analysis of sensor data is a vital part of the CBM System. The CBM data architecture and ground based equipment used to interface with the data should be capable of supporting several types of management actions that support optimal maintenance scheduling and execution:

- Granting CBM credits (changes to scheduled maintenance) based on usage monitoring, damage accrual or CI/HI values, requires accurate configuration management of components and parts installed on the aircraft.

- Ordering parts, based on exceeded CI/HI thresholds that indicate the presence of a fault, requires an interface of the data from the ground based equipment through STAMIS, SARSS and ULLS-A. This interface should be accomplished to eliminate the need for duplicative data entry. The ground based equipment should be capable of monitoring CI/HIs and using the predetermined "thresholds" or CI/HI values to trigger anticipatory supply actions, optimizing maintenance planning, and enhancing safety by avoiding a precautionary landing/recovery/launch.

- Modifying the usage, (i.e.: fatigue) based on usage calculations for a specific serialized component may require automated changes to be recorded in STAMIS record system.

- STAMIS updates, with data resulting from maintenance actions at the depot and which modify component fatigue life based on remediation actions or other repairs, should be incorporated.

For Army aircraft, tracking of individual serialized items begins at the manufacture through its life cycle and is accomplished by either manual records and/or an electronic log book, which is an integral part of the STAMIS architecture. CBM credits can be given to groups of aircraft or parts, as long as they can be tracked. No CBM credits for individual items can be applied without accurate tracking of an individual part's installation and maintenance history as reflected in the electronic log book and other records.

5 Specific Guidance

Specific guidance for the CBM System are grouped by the functionality shown in Figure 1, to link the guidance to the overarching ISO and DA architecture for CBM. Sections below briefly describe the elements of the CBM System architecture and link those elements to specific technical considerations for Army Aviation. To enable these technical considerations to be easily refined as CBM implementation matures, the technical considerations are grouped into six separate Appendices.

These appendices set forth acceptable means, but not the only means, of compliance with CBM detailed technical elements. They are offered in the spirit of an FAA Advisory Circular. They include:

- Appendix A: Usage Monitoring System Guidance with Flight Data Accuracy and Variability
- Appendix B: Regime Recognition/Flight State Classification with Validation of Regime Recognition Algorithms
- Appendix C: Vibration Based Diagnostics
- Appendix D: Minimum Guidance for Determining CIs/HIs
- Appendix E: Flight Data Integrity
- Appendix F: Fatigue Life Management
- Appendix G: Acronyms

5.1 External Systems

External system data guidance are defined by various STandard Army Management Information Systems (STAMIS). Any system designed to enable CBM on an Army platform should follow the guidance set for these systems.

5.2 Technical Displays and Information Presentation

Technical displays and information presentation to support CBM must be accredited and certified for compatibility with software operating systems. These systems are defined by Logistics Information Systems (LIS) for desktop systems that include other current standards for portable maintenance aids or Interactive Electronic Technical Manuals (IETMs).

5.3 Data Acquisition (DA)

Data acquisition standards for converting sensor input to a digital parameter are common for specific classes of sensors (e.g.: vibration, temperature, and pressure sensors). The same standards extant for this purpose remain valid for CBM application, but with a few exceptions. In many cases, data from existing sensors on the aircraft are sufficient for CBM. Failure modes.

Some failure modes, such as corrosion, may require new sensors or sensing strategies to benefit CBM. In all cases, certain guidance should be emphasized:

- Flight State Parameters: Accuracy and sampling rates must be adequate to effectively determine flight condition (regime) continuously during flight. The intent of these parameters is to unambiguously recreate that aircraft state post-flight for multiple purposes (e.g.: duration of exposure to fatigue damaging states).
- Vibration: Sampling rates for sensors on operational platforms must be adequate for effective signal processing and "de-noising." Vibration transducer placement and mounting effects must be validated during development testing to ensure optimum location. (See Appendix C for additional description of other guidance).
- System-Specific: Unique guidance to sense the presence of faults in avionics and propulsion system components are in development and will be addressed in subsequent versions of this ADS. Similarly, the promise of technology to sense corrosion-related damage in the airframe may mature to the point where high confidence detection is included in the scope of this ADS at a later date.

5.4 Data Manipulation (DM)

Data manipulation (also referred to as signal processing) must be governed by best practice throughout the data processing steps. Standardizing a specific set of practices is ineffective, as each application requires techniques best fitted to its particular needs. Each set of resultant files from raw data to de-noised data, data compression such as Time Synchronous Average (TSA) and Fast Fourier Transform (FFT), feature or CI calculation, and state estimation must be linked to each other to demonstrate a "chain of custody" and also to indicate which set of algorithms were used. As CBM is a dynamic and "learning" system, the outcome of fault detection and estimates of RUL is dependent upon the software modules used. Traceability of this software is essential for configuration management and confidence in the result. Specific guidance for data integrity and data management as described in DO-178[4] and DO-200[5] are listed in Appendix E.

5.5 State Detection (SD)

State Detection uses sensor data to determine a specific condition. The state can be "normal" or expected, an "anomaly" or undefined condition, or an "abnormal" condition. States can refer to the operation of a component or system, or the aircraft (e.g., flight attitudes and regimes). An instance of observed parameters representing baseline or "normal" behavior must be maintained for comparison and detection of anomalies and abnormalities. Sections of the observed parameter data that contain abnormal readings which relate to the presence of faults should be

[4] RTCA DO-178B, Software Considerations in Airborne Systems and Equipment Certification.

[5] RTCA DO-200A, Standards for Processing Aeronautical Data

retained for archive use in the knowledge base as well as for use in calculation of CIs in near real time.

The calculation of a CI should result in a unique measure of state. The processes governing CI and HI development are:

- Physics of Failure Analysis: This analysis determines the actual mechanism which creates the fault, which if left undetected can cause failure of the part or subsystem. In most cases, this analysis is to determine whether material failure is in the form of crack propagation or physical change (e.g.: melting and embrittlement). This analysis determines the means to sense the presence of the fault and evolves the design decisions which place the right sensor and data collection to detect the fault.

- Detection Algorithm Development: The process of detection algorithm development uses the Physics of Failure Analysis to initially select the time, frequency or other domain for processing the data received from the sensor. The development process uses physical and functional models to identify possible frequency ranges for data filtering and previously successful algorithms as a basis to begin development. Detection algorithms are completed when there is sufficient test or operational data to validate and verify their performance. At a minimum, algorithms should provide a 95% confidence in detection of incipient faults and also have no more than a 5% false alarm rate (indications of faults that are not present). Further details in are found in Appendix D.

- Fault Validation/Seeded Fault Analysis: Detection Algorithms are tested to ensure that they are capable of detecting faults prior to operational deployment. A common method of fault validation is to create or to "seed" a fault in a new or overhauled unit and collect data on the fault's progression to failure in controlled testing (or "bench test") which simulates operational use. Data collected from this test are used as source data for the detection algorithm, and the algorithm's results are compared to actual item condition through direct measurement.

Anomaly detection must be able to identify instances where data are not within expected values and flag those instances for further review and root cause analysis. Such detection may not be able to isolate to a single fault condition (or failure mode) to eliminate ambiguity between components in the system, and may form the basis for subsequent additional data capture and testing to fully understand the source of the abnormality (also referred to as an "anomaly."). In some cases, the anomaly may be a CI reading that is created by maintenance error rather than the presence of material failure. For example, misalignment of a shaft by installation error could be sensed by an accelerometer, with a value close to a bearing or shaft fault.

Specific guidance for general CIs and HIs are found in Appendix D. Because many faults are discovered through vibration analysis, guidance for vibration-based diagnostics are found in Appendix C.

Operating state parameters (e.g.: gross weight, center of gravity, airspeed, ambient temperature, altitude, rotor speed, rate of climb, and normal acceleration) are used to determine the flight regime. The flight environment also greatly influences the RUL for many components. Regime recognition is essentially a form of State Detection, with the state being the vehicle's behavior and operating condition. Regime recognition is subject to similar criteria as CIs in that the regime should be mathematically definable and the flight regime should be a unique state for any instant, with an associated confidence boundary. The operating conditions (or regime) should be collected and correlated in time for the duration of flight for use in subsequent analysis. For specific guidance regarding regime recognition, refer to Appendix B.

For CIs that are sensitive to aircraft state or regime, maintenance threshold criteria must be applied in a specific flight regime to ensure consistent measurement and to minimize false alarms caused by transient behavior.

5.6 Health Assessment (HA)

Using the existence of abnormalities defined in State Detection (SD) (paragraph 5.5), this portion of the CBM System rates the current health of the equipment.

> Health Indicator (HI): An indicator of the need for maintenance action resulting from the combination of one or more CI values.

Health assessment is accomplished by the development of HIs or indicators for maintenance action based on the results of one or more CIs. HIs should be indexed to a range of color-coded statuses such as: "normal operation" (green), "prepare for maintenance" and "conduct when optimal for operations" (yellow), and "maintenance action required" (red). Since it is probable and highly likely that more than one fault will be present in an aircraft at any given time, HIs should also be weighted or ranked based on the fault criticality defined by Failure Modes and Effects Criticality Analysis (FMECA) or other means as part of the SD process. For example, the presence of a fault in the bearing on a redundant electrical generator should be ranked or weighted less severely than a bearing fault in the main transmission. Each fault should contribute to the determination of the overall health of the aircraft. Status of the equipment should be collected and correlated with time for the condition during any operational cycle.

5.7 Prognostics Assessment (PA)

Using the description of the current health state and the associated failure modes, the PA module determines future health states and RUL. The estimate of RUL must use some representation of projected usage/loads as its basis. RUL estimates must be validated during system test and evaluation, and the estimates should show 90% or greater accuracy to the failures observed in seeded fault testing.

For Army Aviation CBM, the prognostics assessment is not required to be part of the onboard system.

The goal of the PA module is to provide data to the Advisory Generation (AG) module with sufficient time to enable effective response by the maintenance and logistics system. Because RUL for a given fault condition is based on the individual fault behavior as influenced by projected loads and operational use, there can be no single criteria for the lead time from fault detection to reaching the RUL. In all cases, the interval between fault detection and reaching the removal requirement threshold should be calculated in a way that provides the highest confidence in the RUL estimate without creating No Evidence of Failure (NEOF) rates higher than 5% at the time of component removal.

5.8 Advisory Generation (AG)

The goal of AG is to provide specific maintenance tasks or operational changes required to optimize the life of the equipment and allow continued operation. Using the information from the Health Assessment (paragraph 5.6) and Prognostics Assessment (paragraph 5.7) modules, the advisories generated for a CBM system must include:

- provisions for denying operational use ("not safe for flight")
- operational limitations in effect until the system is restored
- specific maintenance actions required to restore system operation
- CBM credits for continued operation when the credits modify the interval to the next scheduled maintenance action.

The interval between download of data and health assessment is affected by operational use and tempo or conditions noted by the flight crew. Download is expected at the end of daily operations or at the end of the longest interval of continuous flight operations, whichever is greater.

Defining the basis for continued operation by limiting the qualified flight envelope or operating limitations is determined by the process of granting Airworthiness Credits. Since these limitations are situation dependent, analysis by AED staff engineers is normally required and considered outside the scope of the CBM System to provide through automated software.

5.9 Guidelines for Modifying Maintenance Intervals and Component Retirement Times

A robust and effective CBM System can provide a basis for modifying maintenance practices and updating estimates of fatigue life and component retirement life. As part of the continuous analysis of data provided by the system, disciplined review of scheduled maintenance intervals for servicing and inspection can be adjusted to increase availability and optimize maintenance cost. Similarly, the data can be used to modify the maximum Time Between Overhauls (TBO) for affected components. Finally, CBM data can be used to transition scheduled maintenance to condition based maintenance in a manner that does not modify the baseline risk associated with the aircraft's certification.

5.9.1 Modifying Overhaul Intervals

There have been general guidelines in place for extending TBO's for unmonitored aircraft for many years via "lead the fleet" programs, etc. Typical extensions have been granted for 250 hour intervals based on the successful completion of a minimum of 5 teardown inspections on components at or near their current TBO, all from different aircraft. The number of teardowns and extension interval allotments are a function of the criticality of the component and may therefore vary in some cases. In general, TBO extensions are limited by the calculated fatigue life of the component, unless the failure mode is detectable utilizing a reliable detection system and will not result in catastrophic failure within a short period of time (i.e. no failure within 2 download intervals). In these instances, not only may the calculated life be exceeded but a larger TBO increase may also be possible. For the CBM program, TBO increases may be used as a valuable tool for accumulating the data needed to show reliability/confidence of the monitoring system.

In the case of vibration monitoring, when the condition indicator (CI) limits have not yet been validated, incremental TBO increases of 250 hours, with a minimum of 5 teardown inspections, is appropriate for components at or near their TBO (i.e. green CI). The results of these 5 teardowns should confirm that the hardware condition is representative of a CI "true negative" signature (i.e. green) and that the components meet all existing service inspection limits.

TDA's will be ongoing for components exceeding initially established CI limits. Once the CI limits (red/yellow/green) have been verified based on actual hardware condition, TBO increases of 500 hour intervals are recommended

5.9.2 Transitioning to On-Condition

Guidelines for obtaining on-condition status for components on monitored aircraft having performed seeded fault testing versus data acquisition via field faults are outlined in paragraphs 5.9.3 and 5.9.4, respectively. Achieving on-condition status via field faults could take several years, therefore, incremental TBO extensions will be instrumental in increasing our chances of observing and detecting naturally occurring faults in the field. This holds true for components which have had seeded fault testing performed, but also exhibit credible failure modes which were not tested due to time or funding constraints. Credible failure modes will be determined through FMECA and/or actual field data. Damage limits are to be defined for specific components in order to classify specific hardware condition to CI limit through the use of Reliability Improvement through Failure Identification and Reporting (RIMFIRE) or Structural Component Overhaul Repair Evaluation Category and Remediation Database (SCORECARD), Tear Down Analysis's (TDA), 2410s forms, etc. Implementation plans should be developed for each component clearly identifying goals, test requirements and schedule, initial CI limits, and all work that is planned to show how the confidence levels spelled out in paragraph 5.9.5 will be achieved.

A stair step approach, utilizing the TBO interval increase guidelines provided in paragraph 5.9.1, should be implemented for each monitored component prior to fully implementing on-condition. This will increase the confidence in the monitoring system and ensure the component is behaving as predicted.

5.9.3 Seeded Fault Testing

Seeded fault testing will dramatically reduce the timeline for achieving on-condition status because it requires less time to seed and test a faulted component than to wait for a naturally occurring fault in the field. However, if during the seeded fault test program a naturally occurring fault is observed and verified, it can be used as a data point to help minimize the required testing. Test plans will be developed, identifying each of the credible failure modes and corresponding seeded fault tests required to reliably show that each credible failure mode can be detected. An initial TBO extension could be granted, assuming successful completion of the prescribed seeded fault tests for that particular component. A minimum of three "true" positive detections for each credible failure mode are to be demonstrated by the vibration monitoring equipment utilizing the reliability guidelines specified in paragraph 5.9.5 in order to be eligible for on-condition status. As stated in paragraph 5.9.2, incremental TBO increases should be established prior to fully implementing the component to on-condition status. The number of incremental TBO extensions will be based on the criticality of the component.

5.9.4 Field Fault Analysis

The guidance for achieving on condition status via the accumulation of field faults are essentially the same as those identified in paragraph 5.9.3. Incremental TBO extensions will play a bigger role utilizing this approach based on the assumption that the fault data will take much longer to obtain if no seeded fault testing is performed. A minimum of 3 "true" positive detections for each credible failure mode are to be demonstrated via field faults utilizing the reliability guidelines specified in paragraph 5.9.5 in order to be eligible for on-condition status. As stated in paragraph 5.9.2, incremental TBO increases should be established prior to fully implementing the component to on-condition status. The number of incremental TBO extensions will be based on the criticality of the component.

5.9.5 Statistical Considerations

We are interested in the likelihood that the monitoring system will detect a significant difference in signal when such a difference exists. To validate our target reliability and confidence levels (target reliability = 90%, target confidence = 90%) using a sample size of three possible positive detections, the minimum detectable signal difference is 3 standard deviations from the signal mean.

If at least one of the detections is a false positive, then evaluate to determine the root cause of the false positive. Corrective actions may involve anything from a slight upward adjustment of the CI limit to a major change in the detection algorithm Once corrective action is taken, additional inspections/TDAs of possible positive detections are necessary prior to any additional increase in TBO.

A false negative occurrence for a critical component will impact safety, and should be assessed to determine the impact on future TBO extensions. Each false negative event will require a detailed investigation to determine the root cause.

Components used for TDA and validation may be acquired through either seeded fault testing or through naturally occurring field faults.

5.10 CBM Management Plan

This handbook provides the overall standards and guidance in the design of a CBM system. It is beyond the scope of this document to provide specific guidance in the implementation of any particular CBM design. A written Management Plan or part of an existing Systems Engineering Plan should be developed for each implemented CBM system that describes the details of how the specific design meets the guidance of this ADS.

- At a minimum, this Management Plan is to provide the following:
- Describe how the design meets or exceeds the guidance of this ADS by citing specific references to the appropriate sections of this document and its appendices.
- Describe in detail how the CBM system functions and meets the requirements for end-to-end integrity.
- Specifically describe what CBM credits are sought (i.e., extended operating time between maintenance, overhaul, and/or inspection).
- Describe how the CBM system is tested and validated to achieve the desired CBM credits.

This Management Plan may be developed either by the US Army or by the CBM system vendor/system integrator subject approval of the US Army. The Management Plan should be specified as a contract deliverable to the Government in the event that it is developed by the CBM system vendor or end-to-end system integrator. Also, the Management Plan for CBM design compliance should be a stand-alone document.

6 NOTES

6.1 Additional documents for guidance.

The following documents should be used to compliment the guidance of this handbook.

- Army Regulation 25-2. "Information Management: Information Assurance." 24 October 2007.
- Army Regulation 750–1. "Army Materiel Maintenance Policy." 20 September 2007.
- Army Regulation 750–43. "Army Test, Measurement, and Diagnostic Equipment." 3 November 2006.
- Army Pamphlet 738–751. "Functional Users Manual for the Army Maintenance Management System—Aviation, (TAMMS-A)." 15 March 1999.

- DoDI 4151.22. "Condition Based Maintenance Plus (CBM+) for Materiel Maintenance." Department of Defense Instruction Number 4151.22. 2 December 2007.
- US Army CBM+ Roadmap. Revised Draft 20 July 2007.
- US Army AMCOM Condition Base Maintenance (CBM) Systems Engineering Plan (SEP), Rev: Feb 2008. (Includes Sections 2.2 and 2.3 only.)
- SAE Standard AS 5391A. Health and Usage Monitoring System Accelerometer Interface Specification.
- SAE Standard AS 5392A. Health and Usage Monitoring System, Rotational System Indexing Sensor Specification.
- SAE Standard AS5393. Health and Usage Monitoring System, Blade Tracker Interface Specification.
- SAE Standard AS5394. Health and Usage Monitoring System, Advanced Multipoint Interface Specification.
- SAE Standard AS5395. Health and Usage Monitoring System, Data Interchange Specification.

Appendix A:

Usage Monitoring System Guidance with Flight Data Accuracy and Variability

A.1 Scope

A.1.1 Introduction

There has been a steady evolution of capability to monitor the performance and condition of major systems and subsystems of rotary wing aircraft since the 1970s, with the first installation of a Health and Usage Monitoring System (HUMS) onboard helicopters in the 1990s. Because drive train and engine failure modes are manifested predominantly by increased vibration in a wide range of frequency bands, the assessment of 'health' of a rotary wing aircraft was initially synonymous with low vibration energy levels. As systems became more sophisticated, other parameters, such as engine performance, applied torque and exceedances were included in the list of things to be monitored. Development of HUMS systems have been done by various groups and commercial firms, with limited rigor in definitions or clarity in terminology as to what "health" or "usage" is precisely.

The US Federal Aviation Agency, in its policy PS-ASW100-1999-00063 (released 7/15/1999) makes the following distinctions:

- Health Monitoring: equipment, techniques or procedures by which selected incipient failure or degradation can be determined.
- Usage Monitoring: equipment, techniques and/or procedures by which selected aspects of service [flight] history can be determined.
- Condition Indicator (CI): A measure of detectable phenomena, derived from sensors that show a change in physical properties related to a specific failure mode or fault.

These definitions will be used in this Appendix to clarify and amplify the design requirements for Health and Usage Monitoring of Army aviation items.

In this context, identification of incipient failure or degradation is achieved through the development of CIs which relate changes in physical properties to specific fault modes. CIs are numerical values obtained through the signal processing of data from onboard sensors, which are normally measured and "tagged" with the corresponding time during operation in order to correlate the CI value to the aircraft's state at the time of the reading.. Health monitoring is thus the process of acquiring, analyzing, storing and communicating data gathered to monitor the essential components for safe flight.[6] Developing CIs is fully addressed in Appendix D.

Usage Monitoring, or determination of selected aspects of flight history includes:

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[6] "HUMS: Health Usage and Usage Monitoring Systems." Aviation Maintenance Magazine, 1 February 2006, <http://www.aviationtoday.com/am/categories/military/6134.html>

- Aircraft Configuration: The serialized identity of all designated components as controlled in the 'electronic logbook' plus any other items selected by the PMO. Also, on a mission by mission basis, those items that affect flight loads and aircraft center of gravity. For example, the presence of external stores, position of landing gear, weight of external or internal cargo, fuel quantity. These parameters assist with the determination of flight loads experienced by the airframe and other critical systems

- Flight Environment: altitude, outside air temperature and other parameters that allow reasonable estimation of density altitude.

- Flight Regime: Type of maneuver, its severity (load factor, angle of bank, climb/descent) and duration. Regime recognition is critical to determining flight loads on the airframe and drive systems, and is the subject of Appendix B due to its complexity.

- Aircraft Performance: main rotor speed, applied engine torque and any other parameters which affect loads experienced by the drive system or airframe.

- System Exceedances: Parameters that measure operation beyond normal design conditions which can affect the continued service of a component or system. Examples of exceedances include main rotor overspeed, overtorque of the main transmission and engine over-temperature ("Hot Starts" or operation beyond max continuous temperatures).

By identifying how the aircraft is actually being used, either by individual aircraft tracking or by loads and usage surveys, CBM credits for individual dynamic components or the airframe structure can be more accurately estimated. In addition, Airworthiness Credits can be achieved, (i.e.: Fatigue Life Extension and/or Remaining Useful Life (RUL)), for components that are used less severely than previously assumed, which may reduce operating cost. Likewise, parts flown more severely than previously assumed may be removed and replaced early, thus improving aircraft safety.

This process of life extension (or penalty) based on usage monitoring data is known as the application of Airworthiness credits for continued operation.

Granting of CBM credits (changes to scheduled maintenance) based on usage monitoring requires accurate configuration management of components and parts installed on the aircraft. Airworthiness Credits for fatigue life extension may require more detailed configuration management, including tracking components by par or serial numbers. No CBM credits can be applied without accurate tracking of an individual part's installation and maintenance history.

A.1.2 Purpose

This appendix establishes the minimum technical guidance to ensure the development of an adequate usage monitoring system for Army Air Items. It defines the design, analysis, and validation testing requirements necessary to substantiate that a monitoring system can provide reliable data to support CBM. To maintain generality, this appendix does not specify the logic or equations for any particular set of signal processing methods. However, the appendix does specify how all methods are to be validated through flight testing.

For CBM Systems which employ HUMS to manage structural fatigue, CIs for any given structural component, while important, need not be directly measured as part of CBM. A complete baseline of structural loads for all critical components is measured during the flight loads survey of developmental testing. If the aircraft structural monitoring program includes a complete list of all flight condition that produce critical loads within Regime Recognition, then CBM requirements can be satisfied without direct measurement on all aircraft. The measured flight loads from developmental testing serve as the basis for adjusting fatigue life, which are modified by collecting the actual flight experience and calculating the impact on fatigue life over the assumed mission profiles/mix of the average aircraft.

A.2 Applicable Documents

- "HUMS: Health Usage and Usage Monitoring Systems." Aviation Maintenance Magazine, 1 February 2006. <http://www.aviationtoday.com/am/categories/military/6134.html>
- McCool, K. and Barndt, G. "Assessment of Helicopter Structural Usage Monitoring System Requirements." DOT/FAA/AR-04/3. April 2004.

A.3 General Guidance

The types of usage parameters that are acquired, processed, stored and used to determine the service history of the aircraft can be grouped into five main categories.

- Aircraft Configuration
- Flight Environment
- Flight Regime
- Aircraft Performance
- System Exceedances

A.3.1 Aircraft Configuration

Table A-1 is an example of parameters that define the aircraft configuration. This data is typically collected and maintained in the aircraft electronic logbook with information on serial numbers of each installed end item normally linked to flight data by the HUMS "ground station" or off board data collection and storage software.

Table A-1: Typical Military Helicopter Configuration Items

	General Configuration Items
1	Main Rotor Blades
2	Main Rotor Swashplate
3	Main Rotor Shaft
4	Main Transmission
5	Engines
6	Auxiliary Power Unit
7	Tail Rotor Drive Shafts
8	Intermediate Gear Boxes
9	Tail Rotor Gear Box
10	Tail Rotor Blades
11	Flight Control Actuators
12	Flight Control Rods
13	Electrical Generators
14	Hydraulic System(s) Pumps
15	Landing Gear (s/n for each)
16	Mission/Weapon System Computers
17	EO/IR Sensor Systems Components
18	EW/Defensive Systems Components
	Mission Configuration
19	Ordnance Racks installed
20	Ordnance load (recorded for each flight)
21	External Fuel Tanks installed

The sample list of components above contain subassemblies and individual parts that are also often tracked by serial number to determine operational history, so databases containing configuration information should follow the WUC code structure and serial number tracking requirements set by the initial design specifications.

A.3.2 Flight Environment

Table A-2 shows typical Flight Environment parameters, some of which are important to Regime Recognition as well.

Table A-2: Typical Military Helicopter Flight Environment Parameters

	Local Base Environment – Off Board Data Collection
1	Geographic Location (Lat/Long) (may be classified)
2	Afloat/Ashore (for landing severity and salt water effects)
3	Ambient Temperature - exposure (duration) at extremes
	Operational Environment – Collected On-Board
1	Outside Air Temperature
2	Altitude

Flight Regime parameters include an extensive number of parameters which are fully discussed in Appendix B.

A.3.3 Aircraft Performance Parameters

Aircraft performance parameters that affect the service history are typically those that measure sources of load or stress on operating components. Table A-3 has a list of typical parameters for rotary winged aircraft which are necessarily collected onboard the aircraft during operation.

Table A-3: Typical Military Helicopter Flight Performance Parameters

1	Main Rotor Speed
2	Engine(s) Gas Generator Speed
3	Engine(s) Output Torque
4	Engine(s) Turbine Temperature
5	Engine(s) High Speed Shaft Speed (input to main transmission)
6	Airspeed

These parameters are measured at a sampling rate of at least 8 Hz to ensure that transient spikes are captured,[7] and they are normally recorded in "windows" of time to reduce the total amount of data collected. Because it may not be practical to store continuous history for the duration of the flight, data is often collected in moving 'windows' of sampling, which collects a set of data on a regularly scheduled basis or whenever certain criteria are met (for example, when the rate of change of values are above/below certain rates).

A.3.4 Aircraft Operating Parameter Exceedances

When certain aircraft operating parameters exceed established operating limits, it is important to collect and store that data to facilitate maintenance or inspection of the affected items to ensure continued airworthiness. Such events are known as "exceedances" and can be extremely transitory in nature. The operating limits are defined by the Original Equipment Manufacturer (OEM) and approved by the AED based on initial testing and design specification requirements, and are normally described in the pilot's flight manual for the aircraft. Table A-4 shows some typical exceedances that can affect the condition of helicopter components, and thus require maintenance action. In all cases, the sampled data which measures an exceedance should be able to represent the maximum value obtained and duration of time. During high workload operations the pilot may not be able to sufficiently monitor the aircraft's systems to avoid exceeding an operational limit. When an exceedance occurs, the system must automatically record the level of exceedance and its duration for post-flight evaluation.

[7] McCool, K. and Barndt, G., "Assessment of Helicopter Structural Usage Monitoring System Requirements," DOT/FAA/AR-04/3, April 2004

Table A-4: Typical Military Helicopter Flight Exceedances

1	Main Rotor Speed
2	Engine Gas Generator Speed
3	Engine Output Torque
4	Engine Turbine Temperature
5	Normal Acceleration on landing (hard landing)
6	Normal Acceleration in maneuver (high "g" force)
7	Angle of Bank
8	Maximum Airspeed

A.3.5 Data Storage

Data storage for the parameters discussed above and in Appendices D (Condition Indicators) and B (Regime Recognition) should be sized to meet the guidance. Because operating tempo of Army aviation units can be highly variable, the amount of data to be stored can also be highly variable. A fixed rule for storage should be that the data collection and storage onboard the aircraft in the HUMS system should be capable of storing the data developed during one 24 hour operating period.

The data storage should be accessible during aircraft servicing operations and be capable of downloading all the actionable data stored onboard the aircraft in less than 10 minutes, to preclude data retrieval affecting operational tempo.

A.3.6 System Compatibility

The associated hardware and software used to acquire, analyze, store and communicate data relevant to CBM for army air items must have the following characteristics:

- Sensors: Data collected for CBM should be obtained from sensors already established to the maximum practical extent (for example, cockpit monitoring, power management, navigation). Any sensors added must be able to be powered from existing electrical, hydraulic or pneumatic power sources.

- Data collection: Data transmitted by sensors to onboard data collection hardware must use means that are compatible with existing vehicle systems, such as direct wire (analog signals), MX-1553 Data Bus or Ethernet.

- Analysis and recording hardware must be able to be powered by existing electrical distribution systems and remain within weight and center of gravity allocations assigned by the PM.

- Data Storage Media: data storage and communication through physical media must be accomplished with media that are compatible with existing Army information technology, such as USB memory or CD/DVD read/write discs.

A.3.7 Validation Process for Usage Monitoring

Validation of the collected data described above is accomplished during the developmental/qualification (DT) testing and operational testing (OT) phases of system development. Much of the validation can be done using system components in controlled laboratory environments where the instruments can be verified by a second set of known measurements. For example, main rotor speed can be validated in a test rig by comparing the results to the known standard on the test stand. Similarly, a reference set of instruments attached to the aircraft during DT/OT can be used to verify the readings in the cockpit for virtually all the parameters listed above. Aircraft configuration data can be validated by sampling and auditing the electronic logbook entries to ensure that any changes to part number and serial number are accurately reflected in the corresponding database.

Aspects of validation to ensure that the sensor readings, signal processing filters, and data recording methods collect and deliver the right readings are provided in greater detail in Appendix E.

Appendix B:

Regime Recognition/Flight State Classification with Validation of Regime Recognition Algorithms

B.1 Scope

This Aeronautical Design Standard (ADS) Appendix provides guidance and standards for the development and validation of a method to measure flight regimes of rotary wing aircraft as part of a Condition Based Maintenance (CBM) system for acquiring maintenance credits for onboard components.

B.2 Applicable Documents

The documents listed below are not necessarily all of the documents referenced herein, but are those needed to understand the information provided by this handbook. In addition to the below documents, review of the main ADS (of which this is Appendix B), ADS-79-SP ADS for Condition Based Maintenance for Army Aircraft, for additional guidance in CBM system design should be considered.

B.2.1 Government documents

The following specifications, standards, and handbooks form a part of this appendix to the extent specified herein.

ADS-24. US Army Aeronautical Design Standard – Structural Demonstration for Rotary Wing Aircraft

ADS-29A. US Army Aeronautical Design Standard – Structural Design Criteria for Rotary Wing Aircraft

B.2.2 Other Government documents, drawings, and publications

The following other Government documents, drawings, and publications form a part of this appendix to the extent specified herein.

DOT/FAA/AR-04/3. Assessment of Helicopter Structural Usage Monitoring System Requirements

DOT/FAA/AR-04/19. Hazard Assessment for Usage Credits on Helicopters Using Health and Usage Monitoring System

B.3 General Guidance

In a standard, scheduled maintenance program, component retirement times (CRT) are derived from the total expected exposure to regimes for which flight strain survey data is available. This expected exposure is based on an assumed mission spectrum determined by the class of aircraft. In a CBM system, however, component life calculations can be refined through knowledge of the actual amount of operational time spent in each flight regime. CRTs can be extended when an aircraft is actually exposed to less severe mission profiles and lower flight loads. Or, in the interest of safety, they can be reduced in the presence of higher flight loads than assumed in the original CRT calculations.

The process begins with identifying the set of flight regimes encountered in the mission spectrum for the class of aircraft. For each regime the strain loads are determined during the flight load survey performed during the development phase of the airframe. Next, testing is performed to determine the rate of useful life reduction due to fatigue as a function of time under the regime load for each component for which airworthiness credits are sought by the CBM system. Finally, one must develop an onboard instrumentation package that measures the flight state of the aircraft and accurately classifies the flight regime.

An accurate characterization of the operational flight regime and a conservative estimate to the fatigue reduction in component useful life under load are key characteristics of the CBM system. A dynamic maintenance measurement system should not be implemented that might compromise flight safety in attempt to extend operational life. Therefore, the flight regime classification system must be submitted to a rigorous validation procedure that guarantees component airworthiness credits are not allocated through flight state measurement error, regime misclassification, or a compromise in data integrity.

Usage monitoring is not flight critical; if the system fails, the alternative is to apply the most current Design Usage Spectrum and the associated fatigue methodology for any period of flight time in which the usage monitor data is not available.

B.4 Specific Guidance

B.4.1 Flight Regime Definition

The flight regimes must be identified based on the mission spectrum for a class of aircraft. ADS-29A, Structural Design Criteria for Rotary Wing Aircraft[8] , divides rotor wing aircraft into 3 classes.

> Class I: Those aircraft whose primary mission falls under one of the following general headings: Rescue, evacuation, assault (cargo and troop), liaison, reconnaissance, artillery spotting, utility, training, or antisubmarine.
>
> Class II: Those aircraft whose mission falls under the general heading of cargo and are designed for cargo loading of 5,000 pounds or less,
>
> Class III: Those aircraft whose mission falls under the general heading of cargo and are designed for cargo loading in excess of 5,000 pounds.

[8] ADS-29A – US Army ADS – Structural Design Criteria for Rotary Wing Aircraft.

Note, however, that CBM is not limited to these classifications and may tailor the definitions to achieve optimal performance of classifier algorithms. For example, one may elect to define an attack class of aircraft with a more rigorous set of regimes with specific measurement and classification algorithms.

The specific set of flight regimes should be allocated and approved by the Army, however, the following table (Table B-I) is a candidate set for Class I (Utility) helicopters:

Table B-I: Typical Military Class I (Utility) Helicopter Regimes

1	Rotor Stopped	26	Symmetric Pullouts
2	Ground Operations/Taxi	27	Rolling Pullouts
3	Taxi Turns	28	Pushovers
4	Lift to Hover	29	Partial Power Descent Entries
5	Normal Takeoff from Ground	30	Partial Power Descents
6	Rolling Takeoffs	31	Partial Power Descent Recoveries
7	Jump Takeoffs	32	Autorotation Entries
8	Hover/Low Speed Flight	33	Steady Autorotation
9	Vertical Climb/Low Speed Flight	34	Autorotation Turns
10	Descending Hover/Low Speed Flight	35	Autorotation Pullouts
11	Normal Takeoff from Hover	36	Autorotation Pushovers
12	Damaging Low Speed Flight	37	Autorotation Recoveries
13	Left Hovering Turns	38	Aerial Refueling (when possible)
14	Right Hovering Turns	39	Normal Decelerations
15	Hover/Low Speed Maneuvering	40	Normal Approach
16	Evasive Maneuvering (up and away)	41	Operational Approach
17	Climbing Flight	42	Side Flares
18	Accelerations	43	Normal Landings
19	Level Flight	44	Roll-on Landings
20	Dives	45	Autorotation Landings
21	Left Sideslips	46	Pedal Control Reversals
22	Right Sideslips	47	Longitudinal Control Reversals
23	Level Turns	48	Lateral Control Reversals
24	Climbing Turns	49	Collective Control Reversals
25	Descending Turns	50	External Loads (when possible)
		51	Rotor Shutdown

ADS-29A (Table B-II) should also be reviewed for additional guidance which defines the following set of flight regimes.[8]

Table B-II: ADS-29A Flight Regime Classifications

Symmetrical Flight
Maximum Speed (straight, rearward, sideward flight)
Symmetrical Dive and Pullout
Symmetrical Pushover
Vertical Takeoff
Level Ground
Sloping Ground
Unsymmetrical Flight
Rolling Pullout with Maximum Control Displacement
Yawing
Braked Dive and Recovery
Auto Rotational Flight
Symmetrical Dive and Pullout
Yawing
Anti-Torque Required for those Aircraft Equipped with Anti-Torque Devices
Nap of the Earth (NOE) Maneuvers
Hover Turns (OGE)
OGE Control Reversals (forward/aft, lateral, pedal)
Sideward Flight Quick Stop
Sideward Flight with Kick out & Acceleration (Left & Right)
Collective Pop-up
Side Flare with Kick out and Acceleration (Left & Right)
Left and Right Sideslip (60 & 90-knots KEAS)
Terrain Turns (20, 40, and 60-knots)
Pedal Turns (20 & 40-knots)
Terrain Pull-up (40 & 60-knots)
Terrain Push-over (40 & 60-knots)
Acceleration to 60/V_H to Quick Stop QGE
Air Combat Maneuvers
Gusts
Rotor Starting
Rotor Braking

ADS-29A (Table B-II) provides a detail description of each of the above regimes that includes a quantitative characterization of the range of flight parameters such as airspeed, altitude, and attitude. In the same manner, the CBM designer must clearly, quantitatively define each chosen regime so that classifier algorithms may decisively assign the operation flight time to a flight regime.

B.4.2 CBM Instrumentation Design

B.4.2.1 Onboard Flight State Sensing

A set of measurable flight state parameters should be used as inputs to the regime classification algorithms. A typical set of flight state inputs are provided in Table B-III:

Table B-III: Flight States

	PARAMETER		PARAMETER
1	Pilot's Indicated Airspeed	18	Pitch Rate (INS)
2	Co-Pilot Indicated Airspeed	19	Roll Rate (INS)
3	Outside Air Temperature	20	Yaw Rate (INS)
4	Barometric Pressure Altitude	21	Left Main LG WoW
5	Barometric Rate of Descent	22	Right Main LG WoW
6	Radar Altitude	23	Refueling Probe Ext
7	Normal Load Factor at CG	24	Heading (INS)
8	Main Rotor Speed	25	Roll Attitude (INS)
9	No. 1 Engine Torque	26	Pitch Attitude (INS)
10	No. 2 Engine Torque	27	Trim Ball
11	Average Engine Torque	28	Gross Weight
12	Longitudinal Cyclic Position	29	Increasing Fuel Quantity
13	Lateral Cyclic Position	30	Percent Vh
14	Collective Position	31	Equiv Retreat Ind Tip Speed
15	Directional Pedal Position	32	Elapsed Time
16	Roll Attitude (SGU)		
17	Pitch Attitude (SGU)		

The above list is provided as an example. The implemented list of parameters will be a function of available parameter sources onboard the aircraft and the input needs of the classifier algorithms. However, where possible, one should select natively available flight sensor sources and data buses (such as a 1553 bus) that are available on the aircraft in lieu of adding custom instrumentation. This design decision serves to reduce the cost and complexity of implementation as well as insuring that flight state sensors are guaranteed to be operational and calibrated as part of normal aircraft maintenance procedures.

B.4.2.2 Flight State Sampling Rate

The CBM designer must select the appropriate sampling rate for acquiring flight state parameters. The selected rate must strike a balance between under-sampling with the potential of missing a desired effect and over-sampling which might produce more input than a data collection system can handle. A study for the FAA[9] points out the problem of having a sample rate that is too low. Figure B-1 from the referenced report shows the maximum load factor that would be recorded for a pull-up maneuver at 2 different sample rates.[9] Figure B-1 clearly

[9] McCool, K. and Barndt, G., "Assessment of Helicopter Structural Usage Monitoring System Requirements," DOT/FAA/AR-04/3, April 2004.

illustrates that too low a sample rate will miss the peak of the vertical acceleration and, thus, under-report the severity of the maneuver or, perhaps, not recognize the maneuver at all.

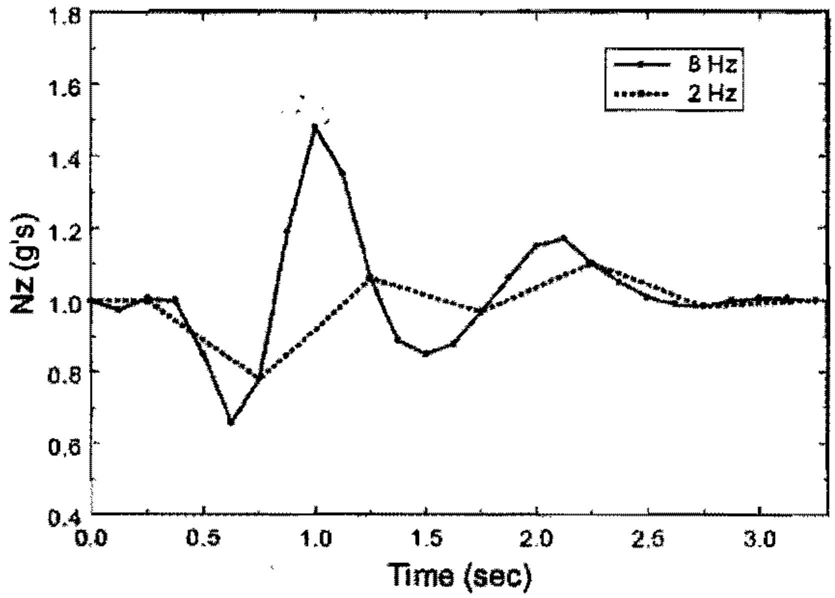

Figure B-1. Effect of Data Rate on Vertical Acceleration[9]

Of course, the primary difficulty in supporting a high sample rate is data storage. One approach to reducing the amount of data acquired is to sample each parameter at its lowest acceptable rate. This requires knowing how quickly parameter values change during a given maneuver, particularly high fatigue damage maneuvers. Table B-IV shows the typical data rates for military helicopters for each parameter. Those parameters not listed in the table, such as outside air temperature (OAT) and barometric altitude can be recorded at 1 Hz.[9]

Table B-IV: Typical Military Aircraft Data Rates[9]

Parameter	Data Rate (Hz)	Max Error
Rotor Speed	6	0.83%
Vertical Acceleration	8	0.13 g's
Pitch Attitude	2	1.8 degs
Roll Attitude	4	2.0 degs
Pitch Rate	4	3.0 degs/sec
Roll Rate	8	2.8 degs/sec
Yaw Rate	4	2.5 degs/sec
Airspeed	2	4.3 kts
Engine Torque	6	3% error
Longitudinal stick position	6	3.1%
Lateral stick position	6	3.9%
Collective stick position	5	3.4%
Pedal position	6	3%
Long. acceleration	6	0.03 g's
Lateral acceleration	7	0.05 g's
Radar altitude	2	13 ft
Vertical velocity	8	242 fpm
Long. Flapping	8	0.61 degs
Lateral Flapping	8	1.0 degs
Lateral swashplate tilt	8	1.1 degs
Long. swashplate tilt	8	1.5 degs

Another approach to reducing data storage is to define bands within the expected range of values for each sensor and record only changes in the sensor bands. Hysteresis is typically used at the boundaries between bands to eliminate frequent toggling between bands at their boundaries.

Data storage can be a significant design issue. Because usage monitoring is not a flight-critical function, the recording unit may not be serviced frequently enough to prevent the loss of data. The recorder should be sized to enable data storage consistent with a 24 hour operating cycle or the longest continuous flight possible, whichever is larger.. The data recording and storage device, along with other HUMS components, should be repaired as soon as practical (even though they are not mission or flight critical), in order to prevent CBM system data degradation. The storage rate may be different from the sampling rate and still meet the needs for CBM.

B.4.2.3 Classification of Flight Regimes

A set of algorithms that use flight state measurements to classify regime and allocate operational flight time to each regime must be developed. The regime classification and allocated flight recording should typically be performed in real-time onboard the aircraft in order to minimize the necessary amount of onboard data storage. However, pending selected sample rates and available onboard data storage capacity, one may elect to store raw, unprocessed fight state measurements for later processing on the ground during maintenance.

B.4.2.4 Component Lifecycle Tracking

In addition to regime classification and flight time tracking, a database system must be developed that accurately allocates regime flight load time to the specific component serial numbers flying on the aircraft. This requires that a database containing indentured parts lists with component serial numbers for each aircraft tail number be maintained as part of the maintenance logistics process. Also, relational integrity checks must be performed as the regime measurement data package is used from the aircraft to update the component ground maintenance records in order to insure that flight time is correctly assigned to the correct component serial number.

B.4.2.5 Data Compromise Recovery

A recovery procedure must be specified for regaining integrity of component ground maintenance records in the event of data corruption or loss. For example, a mismatch occurs in relating the regime measurement data package with a component in the maintenance database or the occurrence of a catastrophic loss of either the measurements or the ground database. The recovery procedure insures that a component serial number is not orphaned without any means of determining its retirement time.

The recovery process may be as simple as maintaining a hardcopy log that records when a component serial number was put in service. The CBM management plan should address the process when an event of CBM system data loss or corruption occurs. An acceptable approach is to account for the time lost using the damage rate produced by the design usage spectrum, as updated throughout the life cycle of the aircraft. For example, if a part is rated to 2000 hrs between replacements under a scheduled maintenance program for a given aircraft and an error occurs in component tracking then the part reverts to the 2000 hr replacement schedule and no maintenance credit may be awarded by the CBM system.

One should consider the criticality of the failure associated with a component when specifying a data compromise recovery strategy. A more conservative procedure should be specified when failure consequences or more severe. As a result, the CBM designer may specify a different recovery procedure for every component in the maintenance tracking database. In the worst case, one may specify that a component be replaced immediately when data loss occurs.

B.4.3 CBM Instrumentation Validation

Prior to deploying the flight regime measurement package as part of operational usage monitoring a test aircraft should be instrumented for demonstrating that the algorithms can accurately classify flight regimes. For development programs this can be performed as part of Structural Demonstration Testing (SDT) where the airframe will be exposed to its range of flight regimes as part of evaluating the limits of its performance envelope. For legacy aircraft however, additional testing may be required to cover the full list of CBM specified flight states. This envelope will be much smaller than the SDT envelope.

B.4.3.1 Algorithm Validation Methodology

A series of flights should be performed with a test aircraft that is fully equipped with the regime measurement package and additional recording systems for capturing data needed to evaluate and tune the algorithms.

Engineering should prepare a series of flight cards identifying the maneuvers for which algorithms have been developed. The monitoring flight test engineer should know the sequence in which the pilots are flying the maneuvers and their target severity and duration. After the flight, the data records will be surveyed to determine which maneuvers were adequately detected and which maneuvers require improved algorithms. Algorithm optimization will be performed and a subsequent flight made in a totally different sequence using the improved algorithms. The post flight process will be the same. Usually two optimization flights are adequate but additional flights may be necessary to achieve the desired regime classification accuracy. For aircraft with a very large range in gross weight (GW) it may be desirable to check the accuracy of the algorithms at very heavy and very light GW. Additionally, an aircraft that has a very high altitude mission may require algorithm validation at both high altitude and near sea level conditions.

Finally, without any knowledge of the flight card content, a comprehensive flight card should be developed which incorporates all of the maneuvers for which algorithms have been developed. The regime recognition design must identify the maneuvers flown, their severity and duration, such that 97% of the entire flight time is properly identified.

B.4.3.2 Accuracy

CBM algorithms must demonstrate that they can define 97% or greater of the actual flight regimes. A CBM system fails when it is wrong in characterizing regimes by more than 3% of total testing. Also, for an unknown flight regime, the system must demonstrate that it errs on the side of selecting a more severe load factor regime in the case where it is incorrectly declared. This insures that a component is not allowed to receive maintenance credit where it is not due and therefore allow a component to fly beyond its margin of safety.

Appendix C:
Vibration Based Diagnostics

C.1 Scope

This Aeronautical Design Standard (ADS) appendix addresses Vibration-Based Diagnostics. It covers the use of sensors, acquisition systems, and signal processing algorithms to detect, identify, and characterize faults in rotorcraft mechanical systems. The process involves extracting features from the vibratory data and comparing the feature characteristics to a baseline set of limits (or. thresholds) which indicate the severity of a potential fault. The diagnostic algorithms should also indicate a recommended maintenance action.

Another application for vibration-based diagnostic systems is rotor track and balance, or rotor smoothing, to reduce rotor vibrations. Rotor smoothing is applicable to both the main and tail rotors. Tracking and balancing a rotor is done by adjusting weights, trim tabs, wedges and pitch link length to minimize the rotor's fundamental harmonic vibrations. Rotor smoothing is critical to minimizing loads on life-limited dynamic components in the rotor system, improving aircrew human factors and reducing vibration in non-rotor system components (which reduces vibration induced failures).

Vibration measurements are collected from sensors such as accelerometers and/or velocimeters at periodic intervals under specific aircraft operating conditions. For example, some diagnostic algorithms require that the data be collected while the aircraft is on the ground with blades at flat pitch and full rotor speed. This is done to eliminate the effects of variations in aircraft loading and drive train torque on the characteristic vibration signatures. Raw vibration data from the sensors is collected in the time domain then typically transformed to the frequency domain to obtain the vibration spectrum. The vibration data should be synchronized with at least one tachometer that produces a pulse at the same rate as the fastest rotating component of interest (order ratio analysis). This synchronization process will permit effective filtration of spectral content from other components not of interest for the most accurate calculation of fault features. Features are then extracted from the spectrum and used to calculate the Condition Indicator (CI). One or more CIs may be used to calculate an aggregate Health Indicator (HI). The CIs and/or HIs are then compared to thresholds to specify the component condition and maintenance status.

C.2 Applicable Documents

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- Zakrajsek, J., Dempsey, P., Huff, E., Decker, H., Augustin, M., Safa-Bakhsh, R., Duke, A., and Grabill, P. "Rotorcraft Health Management Issues and Challenges." NASA/TM-2006-214022. February 2006.
- CAP 753. "Helicopter Vibration Health Monitoring: Guidance Material for Operators Utilising VHM in Rotor and Rotor Drive Systems of Helicopters." UK Civil Aviation Authority, Safety Regulation Group. June 2006. See also: <www.caa.co.uk>.
- Ogata, K. "Discrete-Time Control Systems." Prentice Hall: Englewood Cliffs, NJ, 1987.

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- Roemer, M., Dzakowic, J., Orsagh, R., Byington, C., and Vachtsevanos, G. "Validation and Verification of Prognostic and Health Management Technologies." IEEEAC paper #1344. 27 October 2004.
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- Keller, J.A., Branhof, R., Dunaway, D., and Grabill, P. "Examples of Condition Based Maintenance with the Vibration Management Enhancement Program." Presented at the American Helicopter Society 61st Annual Forum, Grapevine, TX. 1-3 June 2005.

C.3 Technical Guidance

The sensor specifications must be appropriate for the amplitude and frequency domain of the component being monitored. These specifications include its bandwidth, dynamic range, and sensitivity. With regard to signal processing, the system's sampling rate must be high enough to avoid aliasing which causes a distortion that can mask or alter a feature signature. If these parameters are not carefully matched to the component of interest, the algorithms which detect and identify the fault will not perform to the required specifications. The detection and identification algorithms themselves should be inexpensive to implement, explainable in physical terms, and be insensitive to extraneous inputs.

C.3.1 Sensor Guidance

The characteristics of analog sensors include sensitivity, dynamic range, linearity, drift, and bandwidth (or useful frequency range). The following guidance is provided for sensors in a vibration monitoring system.

C.3.1.1 Sensitivity

Vibration sensors (accelerometers and velocimeters) should be sensitive enough to measure the smallest amplitude signal generated by an incipient fault at the threshold of detection by the diagnostic algorithm. The sensor should be able to detect this signal at the specified mounting location of the sensor. In addition, the sensor's cross-sensitivity (or "off-axis" sensitivity) should be 5% or less than the "on-axis" sensitivity.

Sensitivity is measured by the magnitude of the output signal corresponding to a unit input of the measured signal along the specified sensitive axis. It may be expressed as the ratio of the incremental output to incremental input, which is essentially a gain (see Figure C-1). Cross-sensitivity is the sensitivity along axes that are orthogonal to the direction of the sensitive axis. High sensitivity and low cross-sensitivity are characteristics of good sensors. [10]

C.3.1.2 Dynamic Range

The dynamic range of the sensor should extend from the lowest signal amplitude required for detection to the largest expected amplitude such that the sensor signal does not saturate over the intended amplitude range of operation. If the amplitude range is dependent upon the location and/or orientation at which the sensor is mounted, the determination of the required dynamic range should take this dependency into account.

The dynamic range of a sensor is determined by the largest and smallest input signals that can be detected or measured by the device. In most cases the lower limit is dictated by the amplifying electronics noise floor and the higher limit by the voltage rail used by the power supply.

C.3.1.3 Linearity

The sensor's amplitude linearity should be 1% or less of full scale. Any associated bracketry required to install the sensor on the component of interest must be considered in the measure of linearity.

Linearity is determined from the sensor's calibration curve which is a plot of the output amplitude versus the input amplitude under static conditions within the dynamic range of the sensor. The degree to which the calibration curve is a straight line is its linearity. Linearity is expressed as the maximum deviation of the calibration curve from the least squares straight-line fit of the calibration data in percent of the full scale range of the sensor.[10]

C.3.1.4 Drift

Sensor drift should be less than 1% over the expected range of ambient operating conditions. If the sensor drift is greater than 1%, then the parameters inducing the drift should also be measured to permit compensation for the drift.

Over a period of time the characteristics of a sensor may change or drift with changes in temperature, pressure, humidity, the power supply, or with aging. Parametric drift is drift that results from parameter changes caused by instrument nonlinearities.[10] Change in a sensor's sensitivity due to temperature changes is an example of a parametric drift.

C.3.1.5 Bandwidth

To ensure adequate sensor response, the bandwidth or useful frequency range of the sensor should exceed the frequency range of interest for the component(s) being monitored.

The bandwidth of a sensor is defined as the frequency range over which the magnitude of the ratio of the output to the input does not differ by more than ±3 dB from its nominal value (see

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[10] deSilva, Clarence, *Control Sensors and Actuators*, Prentice Hall, NJ, 1989, pp. 51-53. [Reference not available.]

Figure C-1). In the case of an accelerometer, for example, the input is acceleration while the output is volts. Thus the magnitude ratio is in the form of volts/g which varies by no more than 3 dB over its bandwidth.

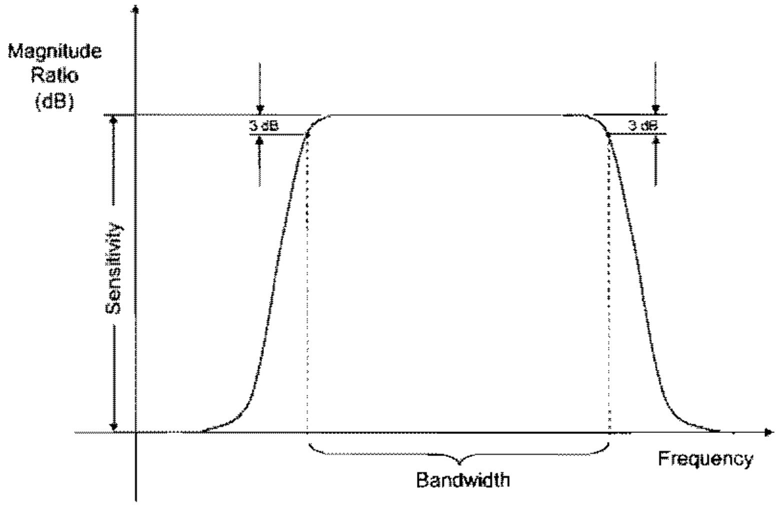

Figure C-1. Sensor Response Characteristics

C.3.1.6 Installation

Vibration sensors should be mounted as close as practical to the component(s) they are intended to monitor. In addition, they should be oriented such that their sensitive axis is aligned with the predominant axis of vibration. Each proposed mounting location should be tested (e.g. rap test and during dynamic developmental testing) to characterize the natural structural response at the mounting location. No mounting locations should be used that have structural resonance frequencies that can mask the frequency modes of the dynamic components being monitored.

C.3.1.7 Built-In Test Capability

The vibration monitoring system should have a capability for verifying the proper functioning of the sensor circuitry.

C.3.2 Data Acquisition and Signal Processing Guidance

Data acquisition deals with how frequently and under which conditions data sets are acquired. Signal processing is required to convert the sensor's analog signal to a digital signal for computation processing in the diagnostic algorithms. In addition, prior to conversion, the analog signal may require filtering to improve the signal to noise ratio, scaling to improve sensitivity, or adjustments to account for biases due to drift. Care must be taken in signal handling so as not to induce unwanted distortion of the signal.

C.3.2.1 Data Acquisition Conditions

Time series data should be acquired under operating conditions with the greatest signal stationarity. Stationarity denotes the consistency of a signal's statistical properties over time. Conditions with the greatest stationarity may occur when the aircraft is on the ground with the main rotor at full speed and flat blade pitch or in the forward climb regime. [11] Collecting data under conditions of greatest stationarity minimizes the effects of loads variations on the quality of the signal. If the CI for a component requires conditions of high torque or a range or torque levels, this may affect the algorithm's ability to meet performance metrics related to false alarm rate, detecability and accuracy.

C.3.2.2 Data Acquisition Frequency

At a minimum, at least one data set should be acquired for all monitored components for flights of 30 minutes or longer. This data should be acquired under stabilized conditions without the need for pilot action during the flight.[12] In addition, some components, such as high speed rotating parts, may experience a rapid onset of failure, on the order of a few hours. Data for these components should be acquired at frequent enough intervals to allow for fault detection and warning with preventative actions prior to the component's failure.

C.3.2.3 Analog to Digital Conversion

Range: The analog-to-digital converter (ADC) should be chosen to provide adequate range for capturing the expected excursion in signal level without clipping. Clipping or compressing the input signal amplitude induces an artificial modulation into the measured data that can mask or alter the desired feature signature.

Resolution (Dynamic Range): The resolution of the ADC should be sufficient to detect the smallest change in the signal required by the corresponding vibration diagnostic algorithm in the presence of large amplitude background.

Resolution is the smallest change in a signal that can be detected and accurately indicated. It is usually expressed as a percentage of the maximum range of the instrument.[10]

C.3.2.4 Sampling Rate

To avoid aliasing of the sampled signal, the minimum sampling frequency (ω_s) should be at least twice as high as the highest frequency of interest (ω_1) in the signal. To preclude the influence of signal content above frequencies of interest, a prefilter should be used ahead of the sampler to modify the frequency content of the signal before it is sampled so that the frequency spectrum for $\omega > \frac{1}{2}\omega_s$ is negligible.[13]

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[11] Zakrajsek, J., Dempsey, P., Huff, E., Decker, H., Augustin, M., Safa-Bakhsh, R., Duke, A., and Grabill, P. "Rotorcraft Health Management Issues and Challenges," NASA/TM---2006-214022, February 2006.

[12] CAP 753. "Helicopter Vibration Health Monitoring: Guidance Material for Operators Utilising VHM in Rotor and Rotor Drive Systems of Helicopters." UK Civil Aviation Authority, Safety Regulation Group. June 2006. See also: <www.caa.co.uk>.

[13] Ogata, K., "Discrete-Time Control Systems," Prentice Hall, Englewood Cliffs, NJ, 1987, pp. 170-177.

Signal aliasing is the result of higher frequencies being folded into lower frequency signals due to the sampling rate being too low. While the minimum sampling rate is required to be twice as high as the highest frequency component present in the signal, this represents the theoretical minimum required to reconstruct the continuous signal from the sampled data. In practice, the sampling frequency is frequently chosen to be $10\omega_1$ to $20\omega_1$.

C.3.2.5 Data Windowing

Digital processing is performed on a "window" of measured data that is often extracted from a continuously occurring event. Windows applied to data to prevent leakage error should be defined in the system performance specification.

Processing of a finite record length of data inherently induces a distortion, called leakage, which can perturb the feature signature and reduce the detected signal-to-noise ratio. Care must be taken in selecting a proper amplitude taper (window) to reduce these effects. Applying no window at all is to imply a rectangular window which can induce high levels of unwanted signal leakage (loss).

C.3.3 Diagnostic Algorithm Guidance

Vibration-based diagnostic algorithms perform two basic functions: anomaly detection and fault isolation. Anomaly detection is the process of classifying the signal as either normal or anomalous. Fault isolation is the process of determining the root cause of an anomalous signal down to the component level.

As an example, if a diagnostic algorithm is intended to detect a crack of 10 mm or larger in a gear tooth, the accelerometer monitoring the transmission and its associated signal processing algorithms must be sensitive enough to measure the vibration caused by a 10 mm crack at the location at which the sensor is mounted

The following paragraphs provide the guidance for vibration-based diagnostic algorithms.

C.3.3.1 Computational Efficiency

In systems employing onboard fault state estimation the detection technique should be sufficiently computationally efficient so that all required algorithms can be executed without incurring system latencies.

In systems where processing is performed off-board the algorithms should be efficient, so that results are available in a timeframe acceptable to the maintainers making repair decisions. If the computational expense is too high for a particular algorithm, then an alternative technique should be used in order to arrive at a realizable implementation to meet the time requirement.

C.3.3.2 Physical Description

The mathematical system of equations that describe the CI should be based in the physics of failure modeling. In addition, the "signature feature" to which the matched filter is "tuned" for extraction should be describable with the physics of failure.

The spectral shape of a CI vibration in frequency domain should be firmly based in the physics of failure characterization of the device or system. A CI selected in an ad hoc fashion based simply on historical observation without being grounded in the theoretical analysis can be risky and will ultimately lead to an implementation that is less than robust. For example, simply stating that, when a particular phenomenon is observed, it has been found experimentally that "X" is the fault and "Y" is the time to until failure may not be stringent enough to yield an implementation that will work reliably in the field. The physical science behind the effect must typically be understood in order to develop a robust detection technique.

C.3.3.3 Robustness

To ensure robustness, CIs should be uncorrelated with other CIs and insensitive to extraneous variables.

A CI must remain constant as other system variables change or, at least, the mathematics of the parametric change in the CI and its signature with other variables must be well understood at the same time that the other variables are sensed, measured, and incorporated into the system design. Ideally, a CI would be distinct and conditionally independent from other system variables and CIs. A distinctly separable phenomenon allows for a more robust implementation with a CI signature that is not the result of a convolution of a number of effects. However, a complex CI may include normalizing data (for example, torque or temperature).

C.3.3.4 Confidence

To ensure confidence in failure detection, CIs should be characterized by large interclass mean distance and a small intraclass variance. A class is representative of a specific failure mode or the base class of normal operation.

To meet small intraclass variance the effect must produce a signature that exhibits a parametric "clustering" in order to arrive at a matched filter that can reliably achieve a detectable signal-to-noise ratio. A feature that exhibits wide signature excursions induces a high degree of mismatch in the filter designed to extract it. A tight parametric clustering improves the confidence level in declaring a fault while a large interclass distance allows for fault classification by insuring that the feature signature will diverge from its normal operating regime as the fault progresses.

C.3.3.5 Algorithm Validation

All vibration diagnostic algorithms should be validated. Algorithms whose failure to detect the faults for which they were designed that would be hazardous to aircraft operation should be validated against direct evidence of a fault. Algorithms that are less critical may be validated against indirect evidence of a fault. For both direct and indirect evidence, the whole system should be validated end-to-end.[14]

FAA Advisory Circular 27-1B (referenced above) defines "end-to-end" as intended to address the boundaries of the Health Usage Monitoring System (HUMS) application and the effect on the rotorcraft. As the term implies, the boundaries are the starting point that corresponds with the airborne data acquisition to the result that is meaningful in relation to the defined credit without further significant processing. In the case where credit is sought, the result must arise from the controlled HUMS process containing the 3 basic requirements for certification as follows:

1) Equipment installation/qualification (both airborne and ground)
2) Credit validation activities, and
3) Institutions for Continued Airworthiness (ICA) activities.

Direct Evidence: If failure of the vibration monitoring algorithm to detect a condition would be hazardous to aircraft operation, then direct evidence should be used to validate the diagnostic algorithm. Examples of highly critical applications include maintenance tasks such as vibration checks for imbalance/misalignment of high energy rotating equipment, fatigue life counting, or going "on-condition" for flight critical assemblies.[14] Direct evidence of a specific fault may come from either seeded fault testing or accelerated mission testing. In addition, actual field data from the entire system may be used if the detailed loading profiles are known and the parameters that are correlated with the progression of the failure are monitored.[15] Because these types of data sets may be costly to develop, they may be supplemented with data from subsystem or component rig tests.

Tests should be representative of the aircraft for which the credit is being sought and of test conditions representing the flight regime that would prevail when data is normally gathered (e g., cruise).[14] Evidence gathered from on-aircraft ground trials or rig-based seeded tests should be valid for in-flight conditions.

Indirect Evidence: In less critical applications indirect evidence may be used. An example of using indirect evidence would be to analyze results from a number of potential failure modes collectively to determine the probability of an undetected failure.[14] The failure criteria may be derived from proven analytical methods, such as finite element modeling and fracture mechanics, in conjunction with sound engineering judgment. The criteria may be validated by analogy with direct evidence gathered on other aircraft types or equipment.

C.3.3.6 False Alert Rate

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[14] FAA AC 27-1B. "Part 27 Airworthiness Standards Normal Category Rotorcraft" FAA Advisory Circular 27-1B, 12 February 2008.

[15] Roemer. M., Dzakowic. J., Orsagh, R., Byington, C., and Vachtsevanos, G., "Validation and Verification of Prognostic and Health Management Technologies," IEEEAC paper #1344, October 27, 2004.

CI and HI based maintenance actions on the aircraft should have a false alert rate of no more than 5%. A false alert is a warning that results in the unnecessary removal of a component or other unnecessary maintenance actions.

C.3.3.7 Missed Detection Rate

Vibration diagnostic algorithms should successfully detect at least 90% of significant (1 in 1,000,000 flight hours) failure modes occurring in the components that the system is designed to monitor. In applications where a missed fault detection could be flight critical to the aircraft's operation, the missed detection rate should be no more than 1 in 1,000,000 occurrences of the fault.

C.3.3.8 Fault Isolation Rate

Once a fault has been properly detected, the fault should be correctly isolated 95% of the time.[16] Since a component may fail in several ways, the system should isolate and identify the particular type of failure specifically within that component.

C.3.3.9 Software Development

Vibration diagnostic software should be developed, as the minimum, to the integrity level required by the system criticality assessment using RTCA/DO-178B Level D. This system-determined level should be a result of the end-to-end criticality assessment and, in general, the same as the airborne software.[14]

C.3.3.10 Recommended Maintenance Actions

A reliable alert generation process should be developed to advise maintenance personnel of the need to review data and determine what maintenance actions are required.[12] Refer to Appendix D.

C.3.4 Prognostic Algorithm Guidance

Prognosis is the estimation of the time when maintenance action must be taken or when a component will fail within a specified confidence bound (see ADS paragraph 2.2, Remaining Useful Life).

C.3.4.1 Predictability

The feature to be detected and the CI that the detection updates and supports should be amenable to characterization by a mathematical function that enables prediction of future condition. Prognostics based on this characterization will be updated with usage experience.

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[16] Health and Usage Monitoring Metrics, Monitoring the Monitor, SAE Aerospace, Aerospace Recommended Practice ARP5783, Jan. 11, 2008. [Reference not available.]

C.3.4.2 Time Horizon Guidance

Prognostic algorithms that predict the time remaining before a required maintenance action and the time until the component will fail should have time horizons of sufficient length to permit the scheduling of maintenance actions and to ensure the safe operation of the aircraft.

In some components incipient failures may be detectable only a few flight hours prior to component failure. This is particularly true of components operating under load at high rotational speeds. Consequently, vibration data acquisition for these components should be performed more frequently than for other components.[12]

C.4 Monitored Dynamic Components

Rotorcraft mechanical systems are predominantly grouped in the engine, the drive system, the accessory subsystems, and the rotor systems. In the engine and drive system the critical faults typically include gear, bearing, and shaft failures. Accessory subsystems, such as electrical and hydraulic systems, also include components typically consisting of gears, shafts and bearings that derive power from the drive system through auxiliary gearing and shafts. The rotor system consists of main and/or tail rotor smoothing (a.k.a. track and balance). The following paragraphs list the CIs that have been developed for the various mechanical system components.

C.4.1 Shaft Condition Indicators

Shaft CIs are mathematically simpler compared to gear and bearing CIs because the shaft faults are detected through simple harmonics of the shaft operating speed. The key indicators of shaft faults can be calculated through either asynchronous or synchronous means, using a synchronous time average (STA). The CIs listed below for shaft faults are proven diagnostics both on test stands and in the field environment. These include:

- Asynchronous Shaft Order ½ (SO½)
- Asynchronous Shaft Order 1 (SO1)
- Asynchronous Shaft Order 2 (SO2)
- Asynchronous Shaft Order 3 (SO3)
- Synchronous Shaft Order ½ (SO½)
- Synchronous Shaft Order 1 (SO1)
- Synchronous Shaft Order 2 (SO2)
- Synchronous Shaft Order 3 (SO3)
- STA RMS
- STA Peak to Peak
- STA Kurtosis

C.4.2 Shaft Balancing and Rotor Smoothing

Shaft balancing and rotor smoothing algorithms are required procedures. Shaft balance is typically accomplished with a magnetic or optical tachometer along with an accelerometer mounted close to the shaft coupling. Rotor smoothing is accomplished with an optical blade tracker, accelerometers mounted in the airframe, and magnetic tachometers.

C.4.2.1 Shaft Balance

Shaft balancing procedures are required on some aircraft platforms. The system may use permanently installed accelerometers to monitor the condition of shafts throughout the drive train, especially shafts operating at very high frequencies (greater than 200 Hz). An example would be the engine output shaft.

Small mass imbalance on a high frequency shaft induces high vibration levels that can be destructive to the surrounding equipment, potentially causing the catastrophic loss of the aircraft. Shaft balance is achieved using a combination of the shaft condition indicators and balancing algorithms. The system should be capable of using linear balance coefficients and applying basic shaft balance techniques.

C.4.2.2 Rotor Smoothing

Rotor smoothing is required on all Army rotorcraft and is an essential maintenance operation. The system may use optical blade trackers to minimize blade track split and accelerometers mounted near the swashplates or in the cockpit in conjunction with a tachometer to reduce once per revolution (1/R) vibration.

Rotor smoothing is accomplished in a step-by-step procedure that involves ground or hover track and lateral balance, and forward flight vibration smoothing. Rotor smoothing algorithms should provide maintainers rotor adjustments such as pitch link changes, hub or blade weight changes, wedges and trim tab changes specific to each aircraft type. Once per revolution (1/R) vibration should be reduced at the most common ground, hover, and forward flight regimes. For aircraft with 4 rotor blades, track should be minimized to reduce the potential for split track conditions typically associated with twice per revolution (2/R) vibration. Rotor smoothing should be accomplished in an average of three flights following phase maintenance.

C.4.3 Bearing Condition Indicators

Bearing faults are typically associated with the rolling elements, cages, and races which make up the bearing and their associated fundamental fault frequencies. Faults also appear as increases in energy bands. In current practice, there are two distinct methods for calculating CIs that use energy based algorithms. The methods differ in their use of an enveloping technique.[17,18] Currently, the US Army National Guard, the US Army Special Operations, and TMDE demonstration program are all using the Vibration Management Enhancement Program (VMEP).[19] The following CIs are for bearings:

- Envelope Ball Energy
- Envelope Base Energy

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[17] Bracewell, R.M. "The Fourier Transform and its Applications", McGraw-Hill, 1965. [Reference not available.]

[18] McFadden, P.D. "Analysis of the Vibration of the Input Bevel Pinion in RAN Wessex Helicopter Main Rotor Gearbox WAK143 Prior to Failure" Aero Propulsion Report 169, Department of Defense, Defense Science and Technology Organization, Aeronautical Research Laboratories. [Reference not available.]

[19] Keller, J.A., et al. "Examples of Condition Based Maintenance with the Vibration Management Enhancement Program." Presented at the American Helicopter Society 61st Annual Forum, Grapevine, TX. 1-3 June 2005. [Reference not available.]

- Envelope Cage Energy
- Envelope Inner Race Energy
- Envelope Outer Race Energy
- Envelope Tone Energy
- Envelope High Frequency Energy (15 – 20 kHz)
- Peak Pick
- Frequency Band Energy

C.4.4 Gear Condition Indicators

The following CIs are laboratory proven on gear test stands operated by various commercial and government organizations.

- Residual Kurtosis
- Residual RMS
- Sideband Modulation
- Narrowband Crest Factor
- Gear Distributed Fault
- G2-1
- Residual Peak to Peak
- Energy Operator
- Sideband Index
- Sideband Level Factor
- FM0
- FM4 & FM4*
- Energy Ratio
- M6A & M6A*
- M8A & M8A*
- NA4 & NA4*
- NA4 Reset
- Amplitude Modulation
- Phase Modulation
- Instantaneous Frequency
- NB4 & NB4*
- NP4

Appendix D:

Minimum Guidance for Determining CIs/HIs

D.1 Scope

This Appendix to the CBM Aeronautical Design Standard (ADS) provides guidance for the development and testing of all Condition Indicators (CIs) and Health Indicators (HIs) used in the Condition Based Maintenance (CBM) System. It includes analytical methods, signal processing software, and data management standards necessary to support their use to implement CBM as the maintenance approach to sustain and maintain systems, subsystems, and components of US Army aircraft.

D.2 Applicable Documents

The documents listed below are not all specifically referenced herein, but are those needed to understand the information provided by this Appendix.

D.2.1 Government Documents

- ISO 13374:2003, Condition monitoring and diagnostics of machines.
- MIMOSA Standard "Open Systems Architecture for Condition Based Maintenance" v3.2, December 2006.
- MIMOSA Standard "OSA CBM for Enterprise Application Integration" v 3.2, December 2006.
- US Army CBM+ Roadmap, Revised Draft 20 July 2007.
- US Army AMCOM Condition Base Maintenance (CBM) Systems Engineering Plan (SEP) Revision – 30 Nov 2007.

D.2.2 Other Documents

- Vachtsevanos, G., Lewis, F.L., Roemer, M., Hess, A., and Wu, B. Intelligent Fault Diagnosis and Prognosis for Engineering Systems. Wiley & Sons: New York, 2006.

D.2.3 Definitions

Condition Indicator (CI): A measure of detectable phenomena, derived from sensors that show a change in physical properties related to a specific failure mode or fault.

Health Indicator (HI): An indicator of need for maintenance action for a component resulting from either a single CI value or a combination of two or more CI values.

D.2.4 Process Description

Condition Based Maintenance (CBM) is a maintenance approach that uses the status and condition of the asset to determine its maintenance needs. CBM is dependent on the collection of data from sensors and the processing, analysis and correlation of that data to maintenance actions.

The processes governing CI and HI development are:

- Physics of Failure Analysis.
- Detection Algorithm Development:
- Fault Correlation Data Mining
- Fault Validation/Seeded Fault Analysis
- Inspection/Tear Down Analysis
- Electronic and Embedded Diagnostics (BIT/BITE)

Related processes that develop estimates of remaining useful life and therefore establish the actions necessary to restore system operation (the objective of HIs) include:

- Failure Prognosis and Health Management Systems Analysis
- Usage Monitoring / Regime Recognition
- Remediation / Remaining Useful Life
- Airworthiness Release for Maintenance Benefits
- Technical Manual Changes

Each of these technical processes are described in detail in the AMCOM CBM System Engineering Plan (SEP) and are subject to review and analysis to ensure that the resulting algorithms and supporting software achieve accurate and repeatable results.

The technical processes described above are used to create a comprehensive and integrated knowledge base which develops effective maintenance tasks and supporting processes necessary to sustain normal operations. The knowledge base changes during the life cycle of the aircraft and serves as the foundation for changes to maintenance practice created by new failure modes, aging effects, and changes to the mission profiles of the aircraft. In addition, as new technology, such as corrosion sensors or improved diagnostics for avionics, becomes proven, new data and detection algorithms will be added to the knowledge base.

D.3 Process Guidance

Detailed Failure Modes Effects Criticality Analysis (FMECA), often completed as a part of Reliability Centered Maintenance (RCM) Analysis, is a favorable starting point for understanding the system, subsystem or component for which the CIs are being developed. Part of this analysis should develop physical and functional models of the system, subsystem and components as a means to determine the likely faults that may arise and their effect on the functions of the various elements of the system.

Models of the fault modes, developed through either simulation and modeling or empirical measurement and analysis through testing should be used to develop first estimates of the fault behavior as it progresses from initiation to failure. This is often described as "Physics of Failure" modeling and analysis. This modeling and analysis is accomplished with the scale and resolution suitable to model the particular fault and item geometry. For example, if crack sizes important to understand the presence and progression of a fault mode, the modeling should be capable of representing crack geometries of the critical crack length as calculated by the analysis. Similarly, if pressure transients of 0.5 psi are important, the model is ineffective if it can only model transients of 2 psi.

If a CBM System design is being undertaken, selecting the most effective faults for inclusion in the effort is normally done in a selection process. From the total population of possible fault modes for all parts, components and subassemblies in the systems of the aircraft, the criticality analysis employed by RCM is used to determine which faults are important enough to equip sensors and data collection for monitoring. While fault modes which affect safety naturally rise toward the top priority for inclusion, fault modes which result in degraded availability and increased maintenance effort can also become high priority for development. The same basis for criticality in RCM analysis applies to CBM, i.e., if RCM analysis has indicated that a particular failure mode requires inspection or remediation, those same modes can be investigated for feasibility analysis for CBM. Fault modes that represent single point failures that have led to the loss of aircraft, death, or major injury are obvious candidates for investigation. Other faults that drive significant costs or readiness degradation are also strongly suitable for CBM feasibility analysis. This feasibility analysis should include trade studies which optimize the cost (weight, system complexity, data collection and processing infrastructure, etc) for the benefit of being able to detect and diagnose the specific fault being considered. There are no fixed or rigid criteria that mandate a particular fault mode as requiring CBM application—the decision to sense and measure data to identify faults and base maintenance decisions on that information is like any other design decision that optimizes cost and risk with benefit.

The results of FMECA and fault models must be used to develop a candidate group of faults for which "features" or characteristics obtainable from signal processing of the data from sensors to detect the presence of the fault modes selected from the above FMECA are feasible. **These "features" are referred to as Condition Indicators throughout this ADS.** This selection process, which is application dependent, establishes the domain of the feature (time, frequency, wavelet, et. al.) and the property of the feature (energy, rms value, sideband ratios, etc) that will be employed to develop the feature (or CI) for use in fault diagnosis.

The FMECA results are also used to consider which faults require feature extraction and CI measurement in flight versus those that can be delayed until after flight. In general, the use of signal processing algorithms and software onboard the aircraft during flight should be limited to:

- Algorithms to compute CIs for faults which are flight critical. Any faults for which the progression could lead to loss of the aircraft in the duration of a normal flight (different for each aircraft) are strong candidates for "onboard" processing. Further ranking of the CIs can be done through risk analysis of the fault likelihood. For example, if one fault has an occurrence of 1 per 100,000 flight hours and another 1 per 10 Million flight hours, inclusion of the former before the latter seems reasonable.

- Algorithms to compute CIs for faults which are combat mission critical. Again, ranking within this category by occurrence factors is the most reasonable approach.

All existing data that provides sensor data responding to both normal operation and failure conditions should be consolidated in a data warehouse for use in algorithm development. Assessing the data to determine data "gaps" can provide insight into any additional testing or modeling and simulation required to support algorithm development.

Performance metrics for the Diagnostic and Prognostic modules should be established for use in the validation and verification of the diagnostic and prognostic algorithms and the maintenance actions and maintenance credits which result. Since the mathematical processes produce results which are estimates of the probability of the existence of faults and RUL, CIs and RUL confidence levels must be established. For CIs this is commonly expressed as a false alarm rate, such as 5% false alarms (detecting the existence of a fault that is not present).

The **Diagnostic Module** must deliver results that provide high confidence determination of the following characteristics: Characteristics of high confidence include:

> **Detectability**: The extent to which the diagnostic scheme can detect the presence of a particular fault. Detectability should relate the smallest failure signature that can be detected at the prescribed false alarm rate.
>
> **Identifiability:** A measure that tracks the ability of the CI to distinguish one fault from another which may have similar properties.
>
> **Accuracy:** A measure of how closely the CI value correlated to the severity of the fault.

Any development of CIs for use in diagnostics should include the metrics above and a validation of those metrics. Only those CIs capable of high confidence detectability, identifiability and accuracy should be used in deployed CBM systems.

Algorithms used to preprocess the sensor data (de-noising, filtering, time synchronous averaging (TSA)) compress and reduce the data necessary to extract or develop the feature or CI used to confirm the presence of a fault. The preprocessing routines, selected for the application, are intended to improve the signal to noise ratio to correspondingly improve the probability of fault detection. Best practice and experience for the specific application may develop guidelines regarding the best range of signal to noise ratio for feature extraction. If those guidelines exist, every effort should be made to develop algorithms consistent with best practice.

The sub-process labeled Detection Algorithm Development (DAD) is often an iterative process that optimizes the data compression filtering and de-noising steps to develop the most effective group of features/CIs to be used as inputs to the diagnostic process. That process can create a feature "vector" or group of individual features/CIs to be used in the diagnostic process to provide the most effective inputs to the diagnostic process. Data from actual failures or seeded fault testing, along with confirmation gained from Inspection/Tear Down Analysis (I/TDA) is used to evaluate the features and optimize their use for diagnosis. The algorithms that calculate each CI can also evaluate the value of the CI against values or "thresholds" that define the fault severity. An individual CI can be assigned values that are "normal" (also referred to as "green"), "marginal" (or "yellow", indicating potential for action such as ordering a part or scheduling a maintenance task) or "abnormal" (or "red"), indicating the need for immediate action). Thresholds can be "hard" or single values (e.g.: bearing energy is normal below 1.25) or "variable" where a range of values is provided (e.g.: marginal is between 3.2-3.3 ips).

High confidence estimation of RUL should follow high confidence identification of the incipient fault and the fault severity which is creating the degradation. If CI values are to be used to assess fault severity, sufficient data from fault validation testing and I/TDA must exist to fully understand the relationship of CI value to fault severity and the progression of fault severity with time. CI values that are not well correlated to fault severity must not be used to estimate RUL.

Prognosis, or the estimation of RUL, forms the basis for projecting the time at which maintenance action must be taken.

Estimation of RUL through "trend analysis" of CI values is only legitimate when:

- Data for the CIs is taken at frequent, regular intervals (application dependent based on the estimated time of failure growth).
- CI behavior with fault progression is not cyclical or highly non-linear.

Prognosis through trend analysis should be biased to yield conservative estimates of RUL, with greater bias for cases where CI severity and failure progression data is incomplete or non-robust.

Estimation of RUL through model-based techniques are legitimate when:

- Baseline data for normal, non-faulted operation exists
- Baseline data for the specific serial number tracked item exists (taken within 10 hours of operation since installation).
- Seeded Fault data exists to sufficiently describe the behavior of the fault under the normal range of operational loading.

The primary metric used to assess prognostic effectiveness is:

Accuracy[20]: A measure of how close a point estimate of failure time is to the actual failure time. Assuming that, for the ith experiment, the actual and predicted failure times are $t_{af}(i)$ and $t_{pf}(i)$, respectively, then the accuracy of the prognostic algorithm at a specific predicting time t_p is defined as:

[20] Vachtsevanos, G., Lewis, F.L., Roemer, M., Hess, A., and Wu, B. *Intelligent Fault Diagnosis and Prognosis for Engineering Systems.* Wiley & Sons: New York, 2006.

$$ACCURACY(t_p) = \frac{1}{N}\sum_{i=1}^{N} e^{-\frac{D_i}{D_0}},$$

where $D_i = |t_{pf}(i) - t_{af}(i)|$ is the distance between the actual and predicted failure times, and D_0 is a normalizing factor, a constant whose value is based on the magnitude of the actual value in an application. N is the number of experiments. Note that the actual failure times for each experiment are (slightly) different due to the inherent system uncertainty. The exponential function is used here to give a smooth monotonically decreasing curve. The value of $e^{-\frac{D_i}{D_0}}$ decreases as D_i increases, and it is 1 when $D_i = 0$, and approaches 0 when D_i approaches infinity. The accuracy is the highest when the predicted value is the same as the actual value, and decreases when the predicted value deviates from the actual value. The exponential function also has higher decreasing rate when D_i is closer to 0, which gives higher measurement sensitivity when $t_{pf}(i)$ is around $t_{af}(i)$ as in normal scenarios. The measurement sensitivity is very low when the predicted value deviates too much from the actual value.

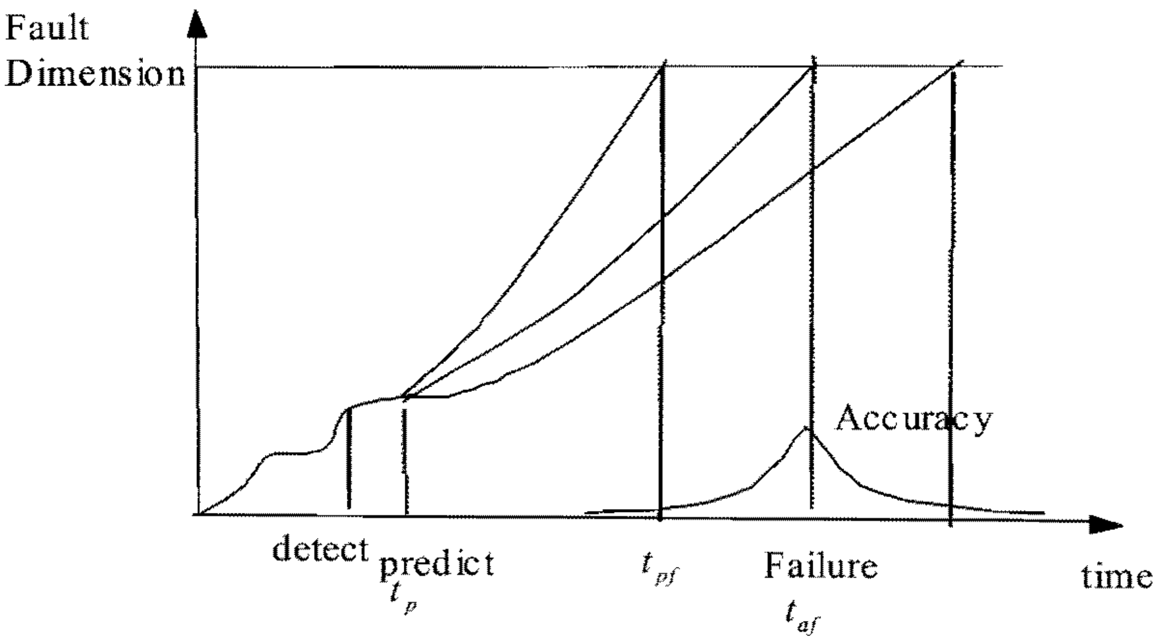

Figure D-1 Schematic of Prognostic Accuracy

Figure D-1 illustrates the fault evolution and the prognosis, the actual and predicted failure times, and the prediction accuracy. Three evolution curves split from the predict time labeled t_p , which represents the time the RUL was calculated, and show 3 possible evolutions of the fault dimension. There is actually a wide range of possible failure evolutions, with a statistical distribution around the actual time to failure, labeled t_{af} as shown along the horizontal axis. The accuracy of the prognostics calculation is the highest (one) when the predicted failure time is equal to the actual failure time. Note that "failure" as defined for prognostics is not limited to the material failure of the item affected by the fault. Failure can be a limit imposed by engineering analysis that prevents catastrophic damage or cascading failures that affect safety or repair cost.

For legacy aircraft, development of a CI can be the result of an emergent requirement, which has been identified by such actions as Accident Investigations or operational experience. In this case, the analysis and development of the CI may be pressed for time and resources. The process of defining the fault mode of interest, the sensor and sensing strategy, algorithm development, CI validation and verification, and Army wide implementation will be a dynamic and tailored process. In some cases, abbreviating the steps associated with CI development may be necessary to meet time constraints. However, even the most urgent development process should follow an organized implementation to ensure that the results are effective.

The processes related to identifying candidate CI and HI should be guided by performance of the results. Since the process of CI and HI development is data driven, there are a number of proven methods to assess the fault detection, isolation and RUL estimation performance. Determining the CI and HI capability to discover the fault early and with high confidence, as well as providing a high confidence estimate of RUL is essential to success for CBM. For a comprehensive discussion on performance metrics, as well as the processes involved with CI and HI development.[20]

D.4 General Guidance

D.4.1 Condition Indicator (CI) Selection

CIs included in the CBM System for a particular Army air item or Unmanned Aeronautical System (UAS) are based on the following criteria:

1) They are identified through Reliability Centered Maintenance (RCM) methods including Failure Modes Effects Criticality Analysis (FMECA) and categorized as:
   - Category 1 – Catastrophic: Faults that could result in death or loss of the aircraft. All Category 1 faults identified in RCM analysis should have CIs developed , unless the forecast rate of occurrence is less than 1 per 10 million flight hours and selected by the AED
   - Category 2 – Severe: Faults that could lead to severe injury or damage to the aircraft. At least 75% of all Category 2 faults should have CI coverage unless the forecast rate of occurrence is less than 1 per 1 million flight hours. The coverage should be allocated to the most frequent faults to the least frequent faults
   - Category 3 – Major: Faults that may result in damage or injury. Included only in cases where the degradation in readiness or cost exceeds thresholds determined by the PM for the aircraft. May also be included if the fault leads to cascading failures of Categories 1

and 2. Coverage for Category 3 faults should be determined from analysis of maintenance costs and readiness and selected by the PM.

2) The CI should be explainable in physical terms, such as bearing failure, shaft misalignment or high temperature.

3) The CI is identified by analysis that considers its functional role in the system as well as its physical properties. The functional analysis describes the impact of degradation or loss of the function on the rest of the component or system. This analysis may include Principle Component Analysis (PCA), a technique that reduces multi-sensor data or data from correlated variables into a smaller set of data which optimizes CI sensitivity and accuracy.

4) The CI is analyzed with respect to the feasibility of sensing the fault; the repeatability of gathering accurate fault data through the sensor; the relative cost or effort required to obtain the CI versus its projected benefit. Any CI that fails to meet these criteria should be eliminated from the development process.

5) The resulting CI behavior should be mathematically definable.

6) The ideal case for a CI is that it should exhibit monotonic behavior (increasing or decreasing with increasing fault size) if the value of the CI is to be used to assess fault severity.

7) The CI should be insensitive to extraneous factors (those unrelated to the fault origin or operational state of the aircraft) or be compensated for in accordance with Appendix C, paragraph 3.3.3.

8) The CI should be capable of detecting the fault as required by engineering analysis to ensure that the fault is detected at the minimum size specified.

9) The CI should be capable of detecting the fault as required with the minimum acceptable level of false alarms and probability of detection. Typical values for false alarms are no more than 5%, depending on fault criticality.

10) The CI should be uncorrelated to other CI values (showing redundant behavior) unless redundancy is beneficial to system performance.

11) The CI should be computationally efficient. The calculation of CIs should be able to meet requirements for timeliness and effective action by maintenance and engineering personnel. For example, computation of CI values should be able to be completed prior to the next flight of the aircraft, in order for maintenance personnel to be able to take the appropriate action to restore system operation to normal.

12) CIs which are derived from proprietary algorithms are authorized as long as: 1) Their general functional description is understood and accepted by the government and 2) the results of the CI are validated, verified and documented during the development process.

D.4.2 Health Indicators (HIs)

HIs are indicators of maintenance action based on the value of one or more CIs. The HI provides the link to the standard maintenance action contained in the appropriate Field Manual (FM) that restores the operation of the system and aircraft to normal levels. HIs serve the function of Health Assessment (HA) in the MIMOSA Standard, as well as Advisory Generation (AG) in the

International Standards Organization (ISO) Standard, as they describe the health of the system and the action to be taken to restore the system to normal.

1) HIs should result in actions that restore system condition with a "first pass" success rate of at least 80%. In other words, the actions linked to the HI must restore the system to Mission Capable status 8 out of 10 times without subsequent repair for the same fault conditions.
2) HIs that combine multiple CI values can use any of the following methods (not intended to be an exclusive list), subject to validation and verification of effectiveness:
    a) Weighted Averages: using weights that modify the straight CI values for criticality and severity
    b) Bayesian Reasoning
    c) Dempster-Schafer Theory: A formalized method for managing uncertainty
    d) Fuzzy Logic Inference
3) HIs that use CI values to assess system health must have a clear understanding of CI correlation to fault growth. The non linear behavior of many faults and corresponding CI values precludes the ability to base actions on simple "trend analysis" which tends to make the fault progression linear.
4) HIs must be compatible with troubleshooting and repair tasks as published in the appropriate FM.
5) HIs that result from ground station post flight processing should integrate with the existing maintenance and logistics information systems (See this ADS main body for additional details). This integration extends to IETMS where applicable.

Appendix E:

Flight Data Integrity

E.1 Scope

This Aeronautical Design Standard (ADS) appendix establishes the guidance for ensuring the Integrity of Flight Data Collection and Storage as a component of any Condition Based Maintenance (CBM) system.

E.2 Applicable Documents

The documents listed below are not necessarily all of the documents referenced herein, but are those needed to understand the information provided by this handbook.

The following specifications, standards, and handbooks (available at <www.rtca.org>) form a part of this appendix to the extent specified herein.

- RTCA DO-178B. "Software Considerations in Airborne Systems and Equipment Certification." 1 December 1992.
- RTCA DO-200A. "Standards for Processing Aeronautical Data." 28 September 1998.
- RTCA DO-278. "Guidelines for Communication, Navigation, Surveillance, and Air Traffic Management (CNS/ATM) Systems Software Integrity Assurance." 5 March 2002.
- RTCA Report: "Future Flight Data Collection Committee Final Report." Issued 4 December 2001.

In addition to these documents, Section 2.1.1 of the basic ADS (of which this is Appendix E) contains others that have general pertinence to the CBM process and should be reviewed.

Note: RTCA documents can be purchased only by members of the organization, whose annual dues are $900 a year.

E.3 Definitions

E.3.1 Data Availability

Data Availability refers to the provisions taken to ensure that the data is available to the maintenance user at the time of need. These provisions include the use of a reliable delivery mechanism as well as storage media.

E.3.2 End-to-End

This term is used within the context of this appendix to mean encompassing the mechanisms from the point at which the data is collected (acquired) to the point in which the data is destroyed including transmission, computation, storage, retrieval, and disposal.

E.3.3 Data Security

Data Security refers to the provisions taken to ensure that the data is protected from corruption by malicious acts.

E.3.4 Data Reliability

Data Reliability refers to the assurances that the data can be used for its purposes in the CBM system as a result of steps taken to ensure its integrity and availability.

E.3.5 Data Integrity

Data Integrity refers to the assurances that the data is unchanged (missing or corrupted) from when it was initially acquired by the CBM system.

E.3.6 Data Verification

Data Verification refers to the steps taken to confirm the integrity of data retrieved from a storage system. These techniques include the use of hash functions on data read-back or the use of a Message Integrity Code (MIC0) or Message Authentication Code (MAC).

E.3.7 Data Reduction

Data Reduction refers to any action taken to reduce the volume of the measured data without compromising the value of the data with regard to its intended purpose. Data reduction is often performed as part of the acquisition process in order to reduce the burden on storage capacity and may be broadly interpreted to actions ranging from downsampling (volume reduction) to filtering (smoothing).

E.3.8 Data Mining

Data Mining refers to reviewing or processing the data in order to obtain information or knowledge. Depending on the format of the stored data, this process can range from signal processing of sampled measurements to queries performed on database tables.

E.4 General Guidance

Condition Based Maintenance systems require the processing and storage of digital data in both aircraft onboard and ground station systems. This data is used to make often critical maintenance decisions regarding the airworthiness and remaining useful life (RUL) of the vehicle, its subsystems, assemblies, and/or components and therefore, must be trustworthy. This appendix describes the system end-to-end design practices to be used to ensure the integrity, reliability, and security of CBM flight data from its onboard acquisition to its ground station storage and usage.

Precautions must be taken at each stage of a CBM system implementation as data integrity can be compromised at any point in the chain from acquisition to storage and retrieval for use. Corruption and/or loss of data may occur during:

- Acquisition
- Onboard computation
- Transmission
- Storage
- Retrieval and use

In addition, the loss of data integrity may be either inadvertent or the result of willful malicious attacks and, therefore, care and handling must include prudent practices that guard against both forms of corruption and loss.

The degree to which data integrity must be ensured is ultimately governed by the severity of the resulting failure or malfunction being prevented by the CBM system. The failure event severity is graded in accordance with the criticality levels prescribed by RTCA DO-178B.[21] The higher the criticality of the failure event being prevented, the more stringent the processes and procedures are to ensure that lack of data integrity is not the cause of poor performance by the CBM system.

E.5 Specific Guidance

E.5.1 Criticality

The measures and procedures taken to ensure data integrity in a CBM system should be determined by the resultant severity of the safety effects caused by a compromise in data integrity. The severity of effects should be determined in accordance with the guidance provided in RTCA DO-178B Section 2.2.1 on Failure Condition Categorization (FCC). These levels are defined as:

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[21] RTCA DO-178B: Software Considerations in Airborne Systems and Equipment Certification.

- Catastrophic: Failure conditions which would prevent continued safe flight or landing.
- Hazardous/Severe: Failure conditions which would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be:

    (1) A large reduction in safety margins or functional capabilities,

    (2) Physical distress or higher workload such that the flight crew would not be relied on to perform their tasks accurately or completely, or

    (3) Adverse effects on occupants including serious or potentially fatal injuries to a small number of those occupants.

- Major: Failure conditions which would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or discomfort to occupants, possibly including injuries.
- Minor: Failure conditions which would not significantly reduce aircraft safety, and which would involve crew actions that are well within their capabilities. Minor failure conditions may include, for example, a slight reduction in safety margins or functional capabilities, a slight increase in crew workload such as routine flight plan changes, or some inconvenience to the occupants.
- No Effect (Non-hazardous class): Failure conditions which do not affect the operational capability or safety of the aircraft, or the crew workload.

Criticality may be determined by performing a Functional Hazard Assessment (FHA). The FHA may be a preliminary document to the Preliminary Safety Assessment (PSA) or a part of the PSA. The FHA is a top down analysis that starts with the hazards to the aircraft and traces these hazards to the system, subsystem, and component level in the areas affected by the CBM system.

For each topic in the following subsections, prevention of corruption and/or loss should be mandatory for data in which failure of that facet of the CBM system could result in Catastrophic, Hazardous/Severe Major, or Major consequences. The prevention of corruption and/or loss of data should be recommended for data in which failure of that facet of the CBM system could result in Minor consequences. No special recommendation on data integrity is made in data for which the failure of the CBM system has no effect. Note, however, the mandated guidance does not preclude implementing a conservative practice which is more stringent than that required to meet the criticality requirement. For example, a design may include password protection and perform routine storage backup of data used in making maintenance decisions on aircraft systems whose failure would not result in catastrophic safety events.

E.5.2 Data Acquisition

Data corruption and/or loss may occur during collection at the point of data initiation; therefore, the necessary precautions should be taken to ensure that data is protected during acquisition. For example, as part of an aircraft onboard data collection system, these precautions will take the form of proper shielding from electromagnetic interference (EMI) in the vicinity of an analog, electrical sensor. Also, any action performed as part of the acquisition process in an effort to reduce the volume of collected data should not compromise the data with respect to its purpose in the CBM system. For example, data should be captured at or above Nyquist rate in order to prevent distortion and any filtering or smoothing should not mask features or characteristics.

In most CBM systems persistent data will ultimately reside in a relational database. Further data acquisition will occur at the ground station as technicians access the data and annotate the records with maintenance actions taken; therefore, the appropriate input protection should be implemented to ensure data integrity. For example, good data acquisition design will incorporate the use of a finite number of selectable options, where possible, as opposed to operator-typed entries. For operator-typed entries the CBM system should perform input data validation in the form of error checking against the defined data schema before presenting input to the database. This would include testing for operator input correctness and completeness, such as preventing entry of a character where a numeric is expected. In addition, the system will perform the appropriate rejected item handling for improper operator entries.

In addition to the user interface of the CBM system software, the relational database management system (DBMS) should be used to ensure data integrity. Data integrity is enforced in a DBMS through the use of integrity constraints and database triggers. An integrity constraint is a declarative method of defining a rule within the DBMS for the column of a table. Examples of integrity constraints are:

- Null Rule: Columns (fields) will disallow INSERTs or UPDATEs to rows (records) containing a NULL (absence of a value) entry.
- Primary Key Rules: Column (field) is identified for containing a "primary key" value that is unique to each row (record). Data entries are disallowed for INSERTs and UPDATEs to rows (records) containing non-unique primary key fields.
- Relational Integrity Rules: A rule defined on a key (column or set of columns) in one table that guarantees that the values in that key match the values in a key in a related table (the reference value). Referential integrity also includes the rules that dictate what types of data manipulation are allowed on referenced values and how these actions affect dependent values. An example of a referential integrity rule is "Set to Default" where when referenced data is updated or deleted, all associated dependent data is set to a default value.

A database trigger is an integrity enforcement rule that refers to a set of database procedures which are automatically invoked on INSERT, UPDATE, or DELETE query operations. Trigger functions performed by the DBMS serve to augment the input testing performed by the user interface of the application software. They are capable of performing more complex tests of the input fields in the course of a database transaction than a simple integrity constraint.

E.5.3 Data Computation

Data corruption and/or loss may occur during computation; therefore, the design should incorporate the necessary precautions to ensure that data is protected during data processing. Typically, integrity tests conducted as part of data processing involve the implementation of "traps" within the application software for error and exception handling. These software traps will include tests for zero divide as well as the improper operator entry and input rejection due to the integrity constraints and database triggers in data acquisition.

Computational data integrity tests will incorporate "try" software blocks (or their syntactic equivalent, depending on software language) for accessing a relational database. In addition to trapping integrity tests, "try" blocks ensure that data is not overwritten while being simultaneously accessed by multiple users in the ground station.

E.5.4 Data Transmission

Data corruption and/or loss may occur during transmission; therefore, the design should incorporate the necessary precautions to ensure data integrity during aircraft onboard and off-board data transmittal. This, for example, will range from EMI shielding of cables used to transmit analog data to procedures for ensuring the integrity of digital information transmitted over a data bus. Digital transmission procedures will range from the use of embedded checksums to the use of error correcting codes for recovering corrupted data. Unrecoverable data lost in the course of transmission may be resolved with protocols such as automatic re-transmission and transmit/receive handshaking.

E.5.5 Data Storage

Data corruption and/or loss may occur during storage; therefore, the design should incorporate the necessary precautions to ensure data integrity during aircraft onboard and off-board storage.

In addition, the design should incorporate proper database administration (DBA) procedures and policies to ensure stored data integrity. These procedures should include the use of routine system-wide data backups performed by the database administrator to prevent catastrophic data loss. Also, the database administrator should perform routine maintenance using a set of database consistency check (DBCC) queries. These queries will include relational integrity checks that identify and fix orphaned records, confirm known record counts within tables, and identify and resolve the existence of multiple primary keys within damaged tables.

E.5.6 Security

In addition to accidental data corruption and/or loss during storage, data integrity may be compromised as a result of malicious attacks on the CBM system. Therefore, the proper design should ensure that security measures and procedures are implemented to prevent the willful, malicious destruction of maintenance data. These measures may include the implementation of either or both physical security and logical security. Physical security refers to the physical placement of the data storage system in a secure area where only authorized administrators have access. Logical security refers to the implementation of user passwords or other authentication for data access. User passwords offer the ability of implementing a layered security by allowing different levels of access, including the ability to change or delete data, to different users.

E.5.7 Data Retrieval

Data corruption and/or loss may occur during data retrieval; therefore, the design should incorporate the necessary precautions to ensure data integrity during data recall from storage and use. For example, modifications to the originally acquired data on retrieval and use should be documented with a date stamp before being returned to storage.

E.5.8 Data Mining

Stored data may be called upon at any time in its lifecycle for processing to obtain information about the observed event. Depending on the nature the stored data, this could involve filtering of sampled measurements or queries of records in a database of processed measurements. Therefore, the data should be oriented and formatted in a manner that allows access to the variety of authorized Army maintenance and analysis systems (see Figure E-1).

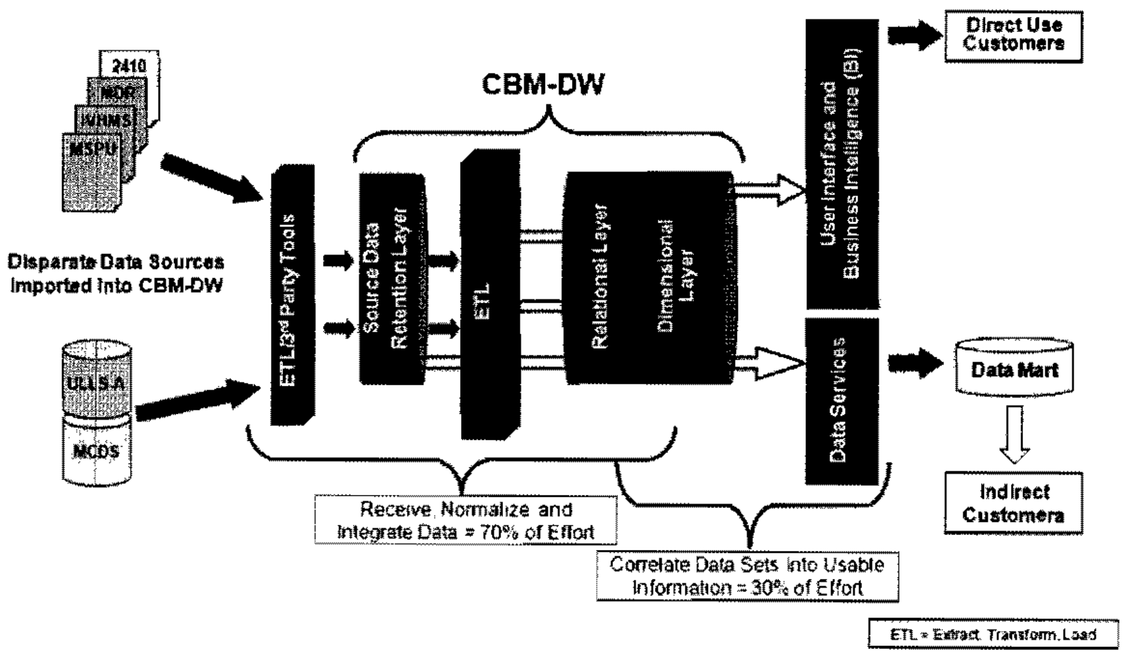

Figure E-1. Data orientation and formatting.

However, as discussed as part of Data Retrieval, measures must be taken to insure that data is not lost or corrupted as a product of data analysis. For example, the data storage system may limit data mining to being performed on a copy of the archived data while retaining the original in order to guarantee integrity.

Appendix F:

Fatigue Life Management

F.1 Scope

The purpose of this appendix is to define the criteria for acceptance of airworthiness credit for incorporation of Condition Based Maintenance (CBM) into Army aircraft from a fatigue life management point of view. This appendix also documents potential applications of CBM.

F.2 References

- Memorandum, Program Executive Officer (PEO), Aviation Policy Memorandum Number 08-03, System Safety Risk Management Process, 20 Jun 2008.

F.3 Introduction

To qualify the structural integrity of an air vehicle, the U.S. Army specifies a Structural Demonstration program and a Flight Load Survey (FLS) program. The structural demonstration tests are used to demonstrate the safe operation of the air vehicle to the structural design envelope. The objective of the FLS is to measure flight loads on the dynamic components. Thus, the typical rotorcraft conditions flown represent the gross weight (GW), center of gravity (CG), airspeed, and altitude combinations representative of the design load conditions. However, Army helicopters are subjected to almost continuous upgrades of capabilities and expansion of missions, creating new critical loading situations which were not flown during the FLS. It is essential that fleet management includes a task that will establish and track the relationship between the original design loads used by the original equipment manufacturers (OEMs) and the loads experienced during operational usage. Conditioned Based Maintenance (CBM) and usage monitoring, using flight recorder data, will provide the information needed to determine and tract this relationship.

A CBM system must provide the capability to measure and record the actual environment (usage, loads, configurations, etc.) experienced by Army aircraft. Through analysis these data can be correlated with established structural integrity methodologies, to establish appropriate maintenance actions.

As explained in the basic ADS (ADS-79-SP), the goals of the CBM system are to reduce burdensome maintenance tasks, increase aircraft availability, improve flight safety and reduces maintenance cost. The primary objective of the CBM process is to enable updating of the usage spectrum required for maintaining airworthiness of Army aircraft.

The secondary objectives include providing:

1) Intervals at which specific component maintenance or replacement actions are required.
2) Usage statistics for each operational command, unit, base or aircraft.
3) The rate at which the fatigue capability of a component is being used and an estimate of the remaining fatigue life.
4) Usage and loads data to support a balanced approach in establishing damage repair limits.

5) Data required for effective Risk Management of the Army's fleet of aircraft. (For example, the loads environment prior to and during a mishap incident provides data required to evaluate the incident and minimize the readiness impact on the fleet.)

It is not the intention of a CBM system to control the manner which Army pilots perform their missions. However, the CBM system will track the loads environment that the aircraft experiences and will adjust retirement lives and inspection requirements based on the severity of the loads environment. Loads variability between pilots performing the same mission is a dominate factor in establishing lives and inspection requirements. Feedback to the user concerning loads severity has a significant potential for reducing maintenance burden and enhancing safety.

The purpose of the following sections (F4.0 thru F4.5) is to provide insight of the Army's expectations of utilizing a CBM system to enhance Fatigue Life Management and Remediation. The Reliability Criteria for establishing maintenance actions based on a CBM system are provided in section 5.0.

F.4 Potential Applications

F.4.1 Updating Design Usage Spectrums

The CBM system provides the capability to update current design usage spectrums of Army aircraft. Refinement with respect to prorating velocity, load factor, angle of bank, sink speed, altitude and gross weight provides greater accuracy in representing actual usage. The number of aircraft required to participate in a usage survey must be statistically significant. Likewise, a survey should be conducted at sufficient locations to ensure inclusion of all missions, including training locations to ascertain appropriate usage severity. When possible, pilot interviews should be conducted in concert with CBM usage data in updating usage spectrums.

The updated usage spectrum provides greater accuracy of current usage. However, the updated spectrum must maintain its intended contribution to component reliability when used to compute retirement lives. Likewise, the impact on reliability for a segment of the fleet must not be compromised through creation of an overall fleet usage distribution. An example of this would be for a small population of the fleet operating at more severe usage (e.g., training aircraft with more GAG and autorotation cycles). The updated usage spectrum may be an updated worse case spectrum or a basic spectrum for the majority of the fleet and a special case spectrum for unique segment of the fleet. The lower retirement time must be used considering interchanging of components and each spectrum must provide the intended reliability contribution.

F.4.2 Managing Service Life of CSI Components

The service life of Critical Safety Items (CSI) on Army rotorcraft is normally managed by a safe life process. The inputs for establishing the safe lives include usage, flight loads and fatigue strength utilizing Miner's linear cumulative damage hypothesis. Although there is no identified safety factor used to ensure the reliability of CSI's reaching their retirement lives without a structural failure, conservative assumptions employed in developing the usage spectrum and flight loads add to the reliability inherent in the fatigue strength curve. Incorporation of the CBM system allows greater certainty of aircraft usage and flight loads severity. Due to this increased certainty, the analysis of CBM data and correlation with component fatigue capability has great potential of achieving CBM goals of reducing burdensome maintenance tasks, increasing aircraft availability, improving flight safety and reducing sustainment costs. Maintenance action enhancement of expensive, low-retirement-life components will deliver the greatest potential service life benefit. The following should be considered when implementing CBM in order to maximize benefits.

- Usage: CBM regime recognition monitoring system will track the maneuvers and aircraft configuration. To properly account for fatigue damage for a flight or mission, fatigue damage should be established for each damaging regime. In addition, maneuver to maneuver damage including GAG must be evaluated and included in total flight damage calculation. In the event the regime recognition monitoring system is not operational, the fatigue damage should be accounted for by applying the worst case assumed fatigue damage determined from the most current design usage spectrum.

- Loads: Maneuver damage assigned to each regime should be based on top of scatter loads (i.e. loads that produce the highest fatigue damage for the regime). Likewise, maximum/minimum loads for maneuver-to-maneuver including GAG cycle should be based on top of scatter loads. For systems that measure both usage and loads, the reliability of the strength curve and/or damage sum methodology must provide the reliability guidance of section 5.

- Fatigue Strength: Fatigue damage should be based using the mean minus 3 sigma ($\mu - 3\sigma$) probability strength with 95% confidence or the baseline S/N curves in the approved fatigue substantiation reports.

- Damage Sum: Fatigue damages sum to less than 1 should be considered to ensure the reliability threshold (i.e. 9_6 component reliability or .01 failure per 100,000 flight hours system hazard) are met.

F.4.3 Remediation

There are myriad reasons why structural components are removed from service before reaching their respective component retirement time (i.e. fatigue life). In fact, the majority of Army components are removed due to damage (nicks, corrosion, wear, etc.) prior to reaching a retirement life. Remediation is the concept of identifying and mitigating the root causes for part replacement in order to obtain more useful life from structural components (including airframe and dynamic components). The safe life process for service life management bases fatigue strength on "as manufactured" components. Damage, repair and overhaul limits are established to maintain component strength as controlled by drawing tolerance limits.

The remediation process provides the means to trade damage tolerance for fatigue life. Utilization of actual usage and loads provides the means to extend the fatigue life at acceptable levels of risk. The steps in the remediation process follows:

1) Categorize and quantify the primary reasons for component removal and decision not to return the component to service.
2) Investigate regime recognition data for casual relations between usage and damage.
3) Perform engineering analysis on the component and evaluate the impact of expanded damage limits on static and fatigue capability. Regime recognition data provides information on load severity and usage for projecting revised fatigue life.
4) Perform elemental or full-scale testing to substantiate analysis.
5) Implement the results of the analysis and testing phase by adjusting damage limits and repair procedures where applicable, thereby increasing the useful life of the component and reducing part removals.

The result is an increase in damage limits in the TMs and DMWRs allowing the component to stay on the aircraft longer. Remediation enhances the four goals of the CBM process and can be considered a subset of the elements; analysis and correlation of data to component fatigue strength

F.4.4 Airframe

The CBM process will provide necessary usage and loads data for continual airworthiness support of airframe structure. The data will be used to develop realistic fatigue usage spectrums for achieving a 0.99 reliability (95% confidence) of meeting the design service life goals without fatigue cracking. It should be noted that this reduced reliability is only for redundant structure that can be substantiated of meeting a $.9_7$ (95% confidence) reliability of a catastrophic failure. These same data will be utilized to help identify inspection requirements (procedure and frequency) to achieve the primary load path reliability. The CBM database will be utilized in the evaluation of existing structure, repairs, beef-ups and redesigns.

Also, the CBM system has the potential to provide real time input to the pilot that airframe fatigue damage is occurring during sustained flight conditions (e.g. level flight). The avoidance of or minimum duration in such a condition will significantly reduce airframe fatigue damage and repair.

Application of the CBM process in airframe structure of Army aircraft has the potential of significant improvements in readiness and reduction of sustainment cost.

F.4.5 Maximizing CBM Benefits

Regime recognition provides the tools necessary to continuously improve aircraft design, maintenance, and safety based on actual usage. Also, the potential exists for enhanced pilot training, improved understanding of regime damage variability and tailored risk management. The CBM management plan should include feedback of results to the user. Analysis of CBM data from a fatigue life management point of view will include the identification of significantly damaging usage and load environments. For systems capable of monitoring the damage severity of a regime (e.g. loads or severity monitoring) the parameters correlating with the degree of damage will be identified. This will allow the preparation of guidance on how to perform maneuvers and missions that are less structurally damaging. Feedback to unit commanders will maximize mission reliability and allow them to better manage their logistic requirements associated with performing each type of mission. The potential exists to extend component lives and to minimize inspection requirements by reducing the severity of the usage environment of Army aircraft.

F.5 Reliability Guidance

The incorporation of a CBM management plan in Army aircraft should not create a system hazard as defined by Program Executive Officer (PEO), aviation policy memorandum number 08-03, System Safety Risk Management Process.[22] Acceptable methods of substantiating this guidance are as follows:

1) Substantiate that the frequency of the system hazard is less than the threshold of the risk matrix (i.e., probability of occurrence is less than .01 per 100,000 flight hours). This is a cumulative frequency of all components managed by the CBM process. Incremental incorporation should require allocation of risk.
2) Substantiate that the incorporation of CBM has not increased the aircraft system level risk.
3) Substantiate that a threshold component reliability of 96 is achieved. This means that the probability of failure for components managed by the CBM process is less than 1 out 1,000,000 components.

[22] Memorandum, Program Executive Officer (PEO), Aviation Policy Memorandum Number 08-03, System Safety Risk Management Process, 20 Jun 2008.

Appendix G:

Composite Definitions and Acronyms

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Composite Definitions and Acronyms

Terms

Airworthiness: A demonstrated capability of an aircraft or aircraft subsystem or component to function satisfactorily when used and maintained within prescribed limits (Ref AR 70-62).

Baseline Risk: The established acceptable risk in production, operations, and maintenance procedures reflected in frozen planning, the Operator's Manuals, and the Maintenance Manuals for that aircraft. Maintenance procedures include all required condition inspections with intervals, retirement lives, and Time Based Overhauls (TBOs).

Condition Indicator (CI): A measure of detectable phenomena, derived from sensors that show a change in physical properties related to a specific failure mode or fault.

Health Indicator (HI): An indicator of need for maintenance action resulting from either a single CI value or a combination of two or more CI values.

CBM Credit: Any change to the regularly scheduled maintenance interval specified by engineering for the affected system, such as an extension or reduction in inspection intervals or maximum operating times established for the baseline system prior to incorporation of CBM as the approved maintenance approach. For example, a legacy aircraft with a 2,000 MOT for a drive system component can establish a change to the MOT for aircraft which are modified with sensors and data collection equipment which allows operation to a higher MOT provided CBM CI values remain below specified limits and the unit remains installed on a CBM equipped aircraft.

Airworthiness Credit: The sustainment or reduction of baseline risk in allowance for a CBM Credit, based on the use of a validated and approved CBM system. The change can be specific to a specific item (component or part), tail number of an aircraft, or any group of items or aircraft as defined in the respective Airworthiness Release (AWR).

Acronyms

AC	Alternating Current
ADC	Analog-to-Digital Converter
ADS	Aeronautical Design Standard
AED	Aviation Engineering Directorate
AG	Advisory Generation
ATTC	Aviation Technical Test Center
AWR	Airworthiness Release
BIT	Build-In Test
BITE	Build-In Test Equipment
BSDGW	Basic Structural Design Gross Weight
CBM	Condition Based Maintenance
CBM+	Condition Based Maintenance Plus
CCV	Constant Coefficient of Variation
CI	Condition Indicator
CLOE	Common Logistics Operating Environment
CNS/ATM	Communication, Navigation, Surveillance, and Air Traffic Management
COTS	Commercial Off-the-Shelf
CRT	Component Retirement Time
CSD	Constant Standard Deviation
CV	Coefficient of Variation
DA	Data Acquisition
DAD	Detection Algorithm Development
DBA	Database Administration
DBCC	Database Consistency Checks
DBMS	Database Management System
DM	Data Manipulation
DoD	Department of Defense
DSC	Digital Source Collector
EMI	Electromagnetic Interference
FAA	Federal Aviation Administration
FCC	Failure Condition Characterization
FDR	Flight Data Recorder
FFT	Fast Fourier Transform
FHA	Functional Hazard Assessment
FM	Field Manual
FMECA	Failure Modes Effects Criticality Analysis

GM	Geometric Mean
HA	Health Assessment
HCF	High-Cycle Fatigue
HI	Health Indicator
HMS	Helmet Mounted Sight
HUMS	Health and Usage Monitoring System
IETM	Interactive Electronic Technical Manual
INS	Inertial Navigation System
ISO	International Standards Organization
IT	Information Technology
KEAS	Knot Equivalent Airspeed
LCF	Low-Cycle Fatigue
LG	Landing Gear
LIS	Logistics Information Systems
MAC	Message Authentication Code
MAGW	Maximum Alternate Gross Weight
MIC0	Message Integrity Code
MIMOSA	Machinery Information Management Open Systems Architecture
MOT	Max Operating Time
MTBF	Mean Time Between Failure
NDI	Non-Destructive Injection
NDT	Non-Destructive Test
NEOF	No Evidence of Failure
OEM	Original Equipment Manufacturer
OGE	Out-of-Ground Effect
OSA-CBM	Open Systems Architecture for Condition Based Maintenance
OT&E	Operational Test & Evaluation
PA	Prognostics Assessment
PCA	Principle Component Analysis
PDO	Performance Driven Outcomes
PEO	Program Executive Officer
PM	Project Manager
PSA	Preliminary Safety Assessment
RCM	Reliability Centered Maintenance
RFP	Request For Proposal
RIMFIRE	Reliability Improvement through Failure Identification and Reporting
RTCA	Radio Technical Commission for Aeronautics
RUL	Remaining Useful Life

SAMS	Standard Army Maintenance System
SARSS	Standard Army Retail Supply System
SAS	Stability Augmentation System
SCAS	Stability Command Augmentation System
SCORECARD	Structural Component Overhaul Repair Evaluation Category and Remediation Database
SD	State Detection
SEP	Systems Engineering Plan
SGU	Symbol Generator Unit
S-N	Stress-to-Cycles
STA	Synchronous Time Average
STAMIS	STandard Army Management Information System
TAMMS-A	The Army Maintenance Management System-Aviation
TBO	Time Between Overhauls
TCP/IP	Telecommunications Protocol/Internet Protocol
TDA	Tear-Down Analysis
TLCSM	Total Life Cycle Systems Management
TMDE	Test, Measurement and Diagnostic Equipment
TSA	Time Synchronous Average
UAS	Unmanned Aerial System
ULLS	Unit Level Logistics System
UML	Uniform Markup Language
UPS	Universal Power Supply
USB	Universal Serial Bus
WoW	Weight-on-Wheels